CURRENTS IN MONTEREY SUBMARINE CANYON

John Edward Hollister

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

CURRENTS IN MONTEREY SUBMARINE CANYON

by

John Edward Hollister

September 1975

Thesis Advisors: R.S. Andrews & R.G. Paquette

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Currents in Monterey Submarine Canyon		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; September 1975 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) John Edward Hollister		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		12. REPORT DATE September 1975 13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Naval Postgraduate School Monterey, California 93940		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Currents
Submarine canyons
Monterey Submarine Canyon

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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(Page 1)

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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The spectral analysis indicated tides as a major driving force of the deep currents, but also indicated the presence of other forcing functions, possibly internal waves, with shorter periods. The coherence between instruments was low, suggesting the possible presence of a near-bottom boundary layer, or that significant signal deterioration was caused by noise.

Currents in Monterey Submarine Canyon

by

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Lieutenant, United States Navy
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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OCEANOGRAPHY

from the

NAVAL POSTGRADUATE SCHOOL

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ACKNOWLEDGEMENT

The author gratefully acknowledges the following persons for their assistance in the preparation of this thesis: Professors Robert S. Andrews and Robert G. Paquette, co-advisors, for their support and advice; Sharon D. Raney of the NPS Computer Center for her hours of programming assistance; Jeannette C. Hollister for her help digitizing data and coding data sheets; the NPS Research Foundation for their generous funding of the research project; Woody Reynolds and the crew of the R/V ACANIA; and Dr. Francis P. Shepard for his time, advice, contributions of equipment, and inspiration.

I. INTRODUCTION

A. PURPOSE

The purpose of this study was to obtain further information about the near-bottom currents and current-related processes in Monterey Submarine Canyon such as turbidity currents, sediment transport, and internal waves. Some aspects of particular interest include: (i) the general character of currents within the canyon; (ii) volume transport at levels 30 m and 60 m above the canyon floor; (iii) power spectral estimates of current directional components; (iv) phase and coherence spectra between vector directional components from the two near-bottom current meters. These computations have not previously been made using time series approximately two weeks in length, obtained from deep portions of the canyon using vertically-arrayed current meters.

B. MONTEREY SUBMARINE CANYON

Submarine canyons are typically rock walled, V-shaped winding valleys, with many dendritic tributaries, that extend seaward across the continental shelf and slope.

Monterey Canyon is the largest submarine canyon on the west coast of the United States, and heads near the center of Monterey Bay at Moss Landing. The canyon heads in unconsolidated sediment, but granite walls appear about 12.8 km seaward at depths of about 640 m.

The canyon is V-shaped, with high, steep walls and rocky outcrops, and has two major tributaries: Soquel Canyon entering from the north at a depth of 700 m and Carmel Canyon, which enters from the south at a depth of 1900 m (Fig. 1).

The gradient of the floor is on the order of 125 m/km in the upper reaches of the canyon. This decreases to 40 m/km at a depth of 91 m and thence remains fairly constant to depths of over 1,220 m [Shepard and Dill, 1966].

Further seaward Monterey Canyon loses its V-shaped walls, becoming broader and more trough-like. At an axial depth of 1,920 m the gradient decreases to 20 m/km, but high, steep walls continue out to a depth of 2,925 m. Here the true canyon terminates, 81.6 km from the canyon head, and becomes the wide, flat bottomed, levee-bordered Monterey Submarine Fan Valley. Cross-sections of the canyon at the investigation site, 1 km up-canyon and 1 km down-canyon from the investigation site, are shown in Fig. 2.

C. PREVIOUS INVESTIGATIONS

Currents in submarine canyons off California were first measured in 1938 by Shepard, Revelle, and Dietz [1939]. These near-floor currents in the canyons off La Jolla, California, were observed to move alternately up-canyon and down-canyon, with variable periods. During numerous descents into the deep canyon in submersibles, Shepard [1967] observed currents moving both up and down the canyon axis with measured speeds of at least 25 cm/sec, fast enough to freely transport fine sand.

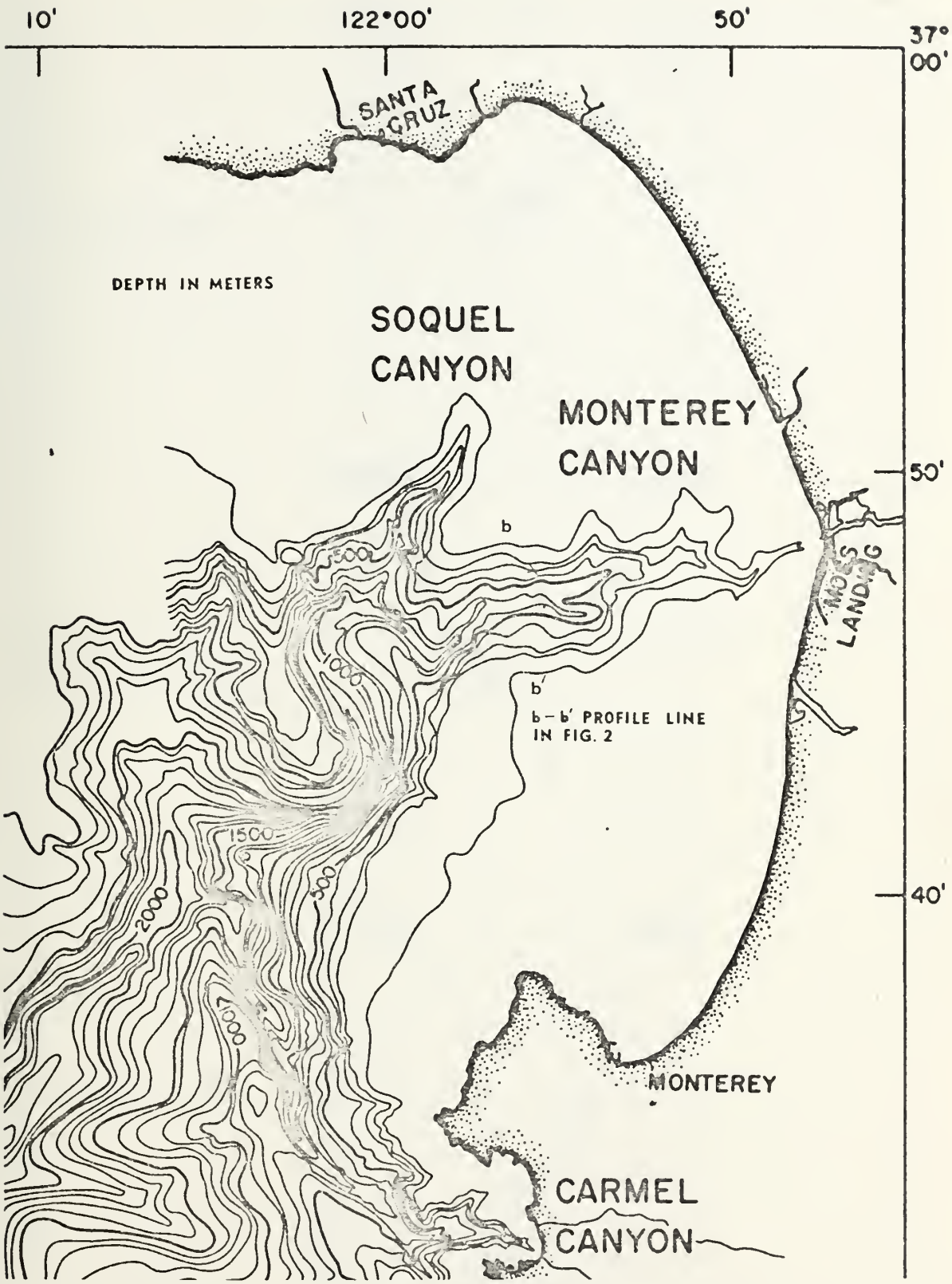


Fig. 1. Monterey, Carmel, and Soquel Submarine Canyons. [From Shepard and Dill, 1966]

a. Up-canyon

b. Investigation Site

c. Down-canyon

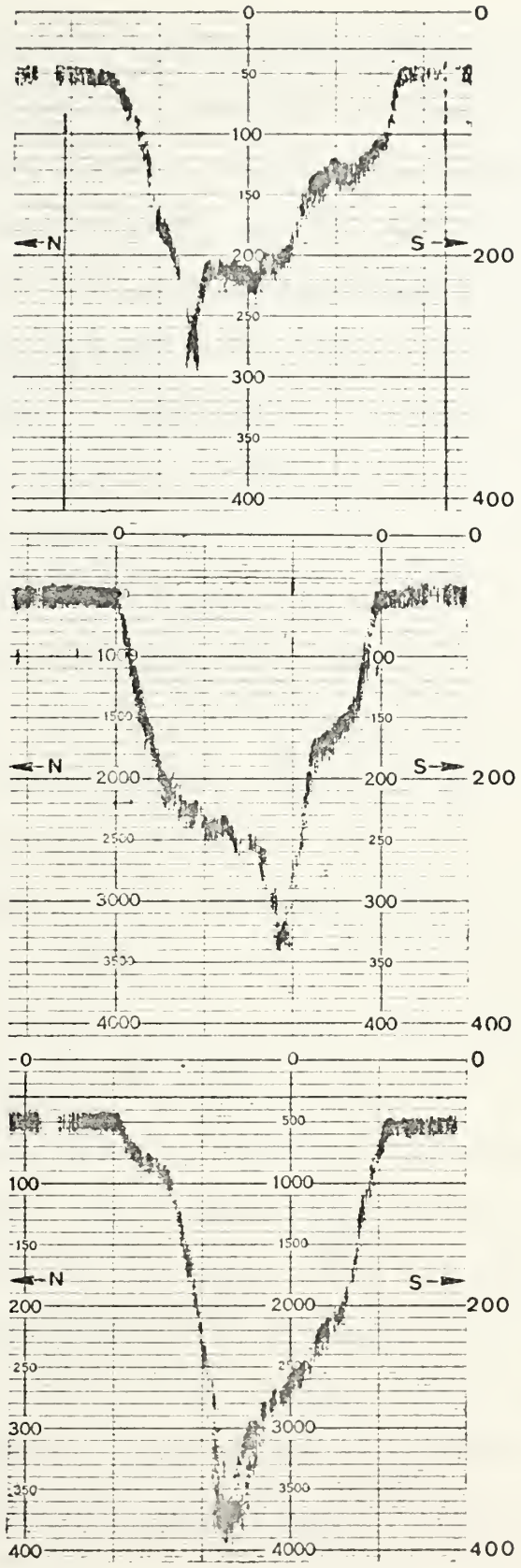


Fig. 2. Cross-sections of Monterey Submarine Canyon (Canyon width 4.4 km).

Indirect evidence of currents comes from photographs of ripple marks on the floors of canyons. In addition, evidence of recent rock erosion directly above the sediment fill on the canyon floors has been observed, such as polished wall rocks and overhanging cliffs, as well as down-canyon sediment creep.

Shepard and Marshall [1969] obtained a series of 3- to 6-day measurements from La Jolla Canyon indicating velocities up to 34 cm/sec with frequent oscillations in direction but far greater net down-canyon movement. No tidal relationships were readily discernible in these early records, but changes in flow from up-canyon to down-canyon were generally slow, virtually all of the higher speed currents occurred during ebb tides, and net water movement decreased with increasing distance above the canyon floor.

Shepard's continuing series of investigations have been conducted using Isaacs-Schick continuously recording Savonius-rotor type meters [Shepard and Marshall, 1969 and 1973b]. These meters were dropped from the surface into axes of submarine canyons and were held in position 3.6 m above the canyon floor by a heavy weight below and a group of floats above. The device was returned to the surface by the release of the bottom weight. Current meters were dropped into La Jolla Canyon at depths from 46 m to 375 m, San Lucas Canyon at 140 m, 220 m and 330 m, Newport Canyon at 100 m and 250 m, Redondo Canyon at 90 m and 250 m, Carmel Canyon at 160 m, and Monterey Canyon at 180 m (Fig. 3).

The canyon currents flowed predominantly in a direction that was parallel, or nearly parallel, to the axis of the

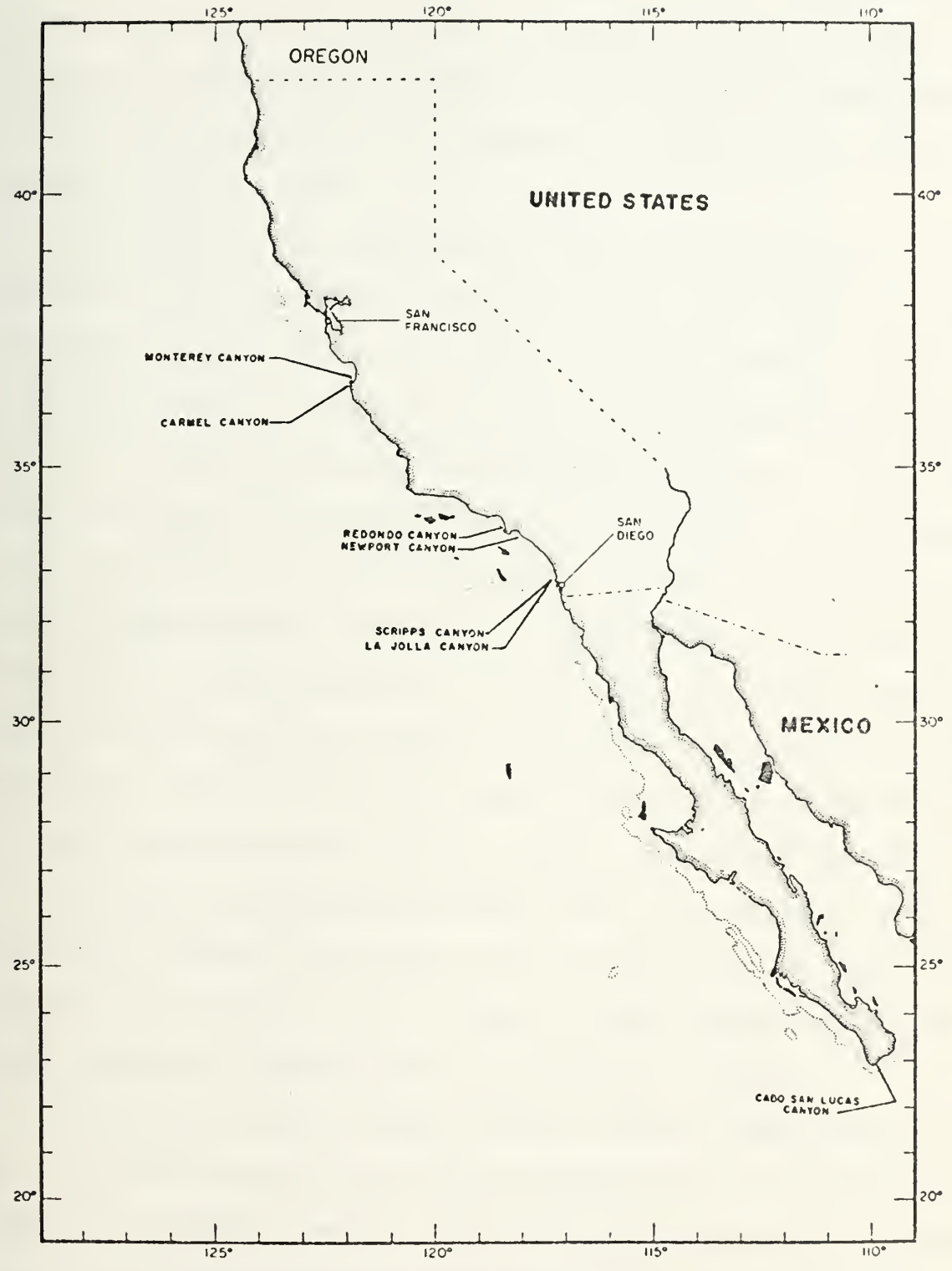


Fig. 3. Location of submarine canyons where current records have been obtained. [From Shepard and Marshall, 1973b]

canyon, and varying up-canyon or down-canyon. The steadiness of direction of up-canyon and down-canyon currents varied considerably from canyon to canyon. In general, however, down-canyon flow appeared to be steadier, perhaps because of its higher velocity (Table I).

The relation of up-canyon and down-canyon cycles to tidal periods is not yet clear, although some of the deeper stations recorded display cycles that are very nearly tidal in period (12 hr, 26 min). Attempts have been made [Shepard and Marshall, 1973b] to compare diurnal and semi-diurnal tides to see if this characteristic variation of Pacific tides has any influence on current cycles; records from a 206 m station in La Jolla Canyon show no appreciable change in the periodicity of flow reversal with the change in character of the tide. A 15-day record from the shallow station at Redondo Canyon was taken while passing through a spring period with semi-diurnal tides, then through a neap period with more nearly diurnal tides, and finally to a less marked spring semi-diurnal tide. The periods of current direction reversal for this record are far shorter than tidal periods and suggest the influence of some other forcing function, perhaps internal waves, at shallower depths.

A vertical array of three current meters above the bottom at the 206 m station in La Jolla Canyon provided information about the current profile. As previously mentioned, currents near the bottom showed a definitely tidal cycle for their peak flows. Currents 19 m and 34 m above the bottom showed similar periods of reversal, but had differing directions of flow.

Canyon Station	Canyon Location	Depth (Meters)	Number Successful Lowerings	Mean Velocity	Highest Velocity cm/sec	% time > 18 cm/sec		Net Transport Meters/hr		Total Directional Flow in Minutes		% Time Direct Flow		Average Length of flows (Min.)	
						Up	Down	Up	Down	Up	Down	Up	Down	Up	Down
1	La Jolla	46	2	1.07	26	.003	0	33.7	0	4,290	3,530	54.9	45.1	65.6	53.5
6	La Jolla	78	2	0.60	17	0	0	26.5	0	5,860	4,260	57.9	42.1	76.0	60.0
5	La Jolla	167	8	1.12	29	.017%	1.24%	0	37.1	20,810	24,090	46.4	53.6	75.0	94.0
3	La Jolla	206	14	2.51	29	.066%	3.23%	0	63.6	31,360	40,450	43.6	56.4	74.0	97.0
10	La Jolla	375	.2	2.08	22	1.29%	0.64%	0	15.8	5,840	6,700	46.5	53.5	216.0	247.0
9	Scripps	125	2	0.85	34	0.65%	1.58%	0	13.9	4,190	5,870	41.6	58.4	47.0	63.0
14	San Lucas	137	3	0.86	17	0	0	0	29.4	2,850	5,540	33.9	66.1	12.0	23.0
13	San Lucas	216	1	0.44	9.5	0	0	0	13.6	1,770	2,890	28.6	71.4	18.0	28.0
15	San Lucas	328	2	3.70	33	0	6.20	0	123.1	2,870	7,190	38.0	62.0	30.0	71.0
20	Newport	101	2	0.92	17	0	0	0	34.1	2,345	2,980	44.1	55.9	87.0	105.0
21	Newport	252	1	0.16	11.5	0	0	0	0	1,010	1,530	39.7	60.2	168.0	255.0
18	Redondo	92	2	1.97	27.0	.006	.011	0	34.2	8,275	12,112	41.5	58.5	87.4	114.9
19	Redondo	283	1	3.19	19.0	.002	0	119.4	0	2,315	820	73.8	26.2	231.0	91.0
11	Carmel	156	1	3.36	20.0	0	0.28%	0	113.9	2,500	4,580	35.3	64.6	71.0	117.0
					TOTALS	2.01	13.18	179.6	468.7	97,065	123,412			1,313.0	1,467.0
					AVERAGES	0.14	0.94	59.8	66.9	6,471	8,827	44.8	55.2	87.5	97.8

TABLE I. Canyon Current Statistics [from Shepard and Marshall, 1973b]

Net flow was decidedly down-canyon at the bottom, at right angles to the canyon at 19 m, and diagonal to the canyon at 34 m. If there is a level at which the direction is reversed, as is suggested by the spiraling directions reported, it appears to be at a height greater than 34 m above the bottom.

Evidence from pairs of stations in La Jolla, Santa Monica, Santa Cruz, Heuneme, Carmel, and Monterey Canyons exists [Shepard, Marshall, and McLaughlin, 1974b] to show internal waves being propagated along the canyon axes, and a close relationship in the direction of flow patterns at various heights above the canyon floors (up to 34 m) has been established. The evidence relating observed currents to internal waves includes the following: (i) the currents oscillate coherently at various heights above the bottom; (ii) the coherently oscillating systems advance along the canyons at velocities greater than the current velocities; (iii) the phase velocity is not correct for surface waves, but is the right order of magnitude for internal waves; (iv) similar types of currents and phase velocities occur on the continental shelf; (v) internal waves move up-canyon in all but one example, which is consistent with the general landward propagation of internal waves across the continental shelf.

By fitting together the current patterns at adjacent stations, displacing one station record relative to the other by a period of time proportional to the distance between the two stations, internal wave propagations speeds of 25 to 88 cm/sec have been calculated.

Although no relation between surface wind conditions and divergence of current flow from the canyon axes could be determined from early records, recent records show strong cross-canyon flows during periods of high cross-canyon wind. These cross-canyon surges also appear to have a tidally-influenced repetition cycle, and have highest speeds and longest durations in canyon areas with broad floors [Shepard, Marshall, and McLaughlin, 1974a].

Gatje and Pizinger [1965] made bottom current measurements in the head of Monterey Submarine Canyon in a water depth of 130 m utilizing an Ekman current meter placed 4.8 m above the bottom. Currents were observed to follow the canyon axes, with seaward flow on the rising tide and coastward flow on the falling tide. Current speed was sometimes fairly steady and other times variable, ranging between 0 and 41 cm/sec and with a median speed of 10 cm/sec. During the 6-hr period centered around low tide the meters recorded currents that were, in general, considerably stronger than the currents recorded during the similar period of time centered around high tide.

An investigation of near-bottom currents in the head of Monterey Submarine Canyon was conducted by Dooley [1968] between March 1967 and May 1968. Continuous observations of water temperature, current speed, and direction were obtained over periods ranging from 5 hr to 162 hr using an internally recording Savonius-rotor current meter. Basic statistical parameters and power spectra were calculated for each record. These revealed an average current speed of about 12 cm/sec

and current directions indicating flow reversals predominantly along the canyon axis. Current and water temperature oscillations indicated a strong semi-diurnal component. Water temperature changes also showed seasonal variation that agreed with the seasonal means of the region. Current speeds as high as 52 cm/sec were recorded.

Njus [1968] made continuous bottom current measurements in the head of Monterey Submarine Canyon at water depths ranging from 146 to 201 m utilizing an internally recording Savonius-rotor current meter placed approximately 12 m above the bottom. Coincident wind, wave, and tide data were obtained along with the current measurements. Basic statistical parameters and power spectra were then computed for each time series. Current speeds in excess of 52 cm/sec were measured, with the current direction being predominantly along the canyon axis. Water temperature, current speed and current direction all exhibited cyclic fluctuations with a periodicity of about 6 hr which, in a presentation of scalar speed, is approximately equal to that of the semi-diurnal tide. Warm, low-speed currents were reported flowing down-canyon on the rising tide. Even though this relation between tidal phase and current direction was also reported by Gatje and Pizinger [1965] it seems somewhat incongruous. One might expect an incoming tidal wave to cause a cold, up-canyon current, but not the opposite.

Average wind speeds were on the order of 10 kt (515 cm/sec) with a characteristic onshore/offshore diurnal variation

and did not appear to have any significant effect on the near-bottom currents. Wave conditions ranged from calm seas to wave periods of 20 sec and heights of about 0.6 m. The longer period, higher-amplitude waves appeared to increase the magnitude of current speeds, but this relationship was not examined in detail.

Caster [1969] measured near-bottom currents in Monterey Submarine Canyon and on the adjacent shelf using Savonius-rotor current meters. Simultaneous measurements were made with one current meter on the shelf at a depth of 91 m and one meter located in the canyon at 366 m. Current speed, current direction and water temperature were recorded continuously for approximately 7 days in each record. Basic statistics were calculated and plotted for these time-series data. Scatter diagrams, progressive vector diagrams and power spectra were also computed and analyzed for the records collected during the study, and for available records of sufficient length from previous investigations.

Net transport was in a cross-canyon direction for many of the records; however, the currents in the canyon oscillated as reported in previous investigations. The oscillations were not as evident on the shelf record. Mean and maximum current speeds recorded in the canyon were 10 cm/sec and 51 cm/sec, respectively. On the shelf these values were 7 cm/sec and 25 cm/sec, respectively. Observed values of net current direction and volume transport on the shelf appeared to be related to Monterey Bay seasonal water conditions.

Current direction was predominantly to the south during the oceanic period and latter part of the upwelling period; however, a northward set was observed during the transition period between the Davidson Current and upwelling periods. Volume transport values changed significantly from the oceanic period.

These earlier investigations have provided a description of the general character of the currents in submarine canyons, with which the results of this investigation may be compared. Most have reported a net down-canyon flow (Table I) and all have noted the tidally-influenced periodicity of flow reversal. Vertically arrayed current meters have recorded current speeds decreasing with distance above the bottom. Previous investigators have emphasized the along-axis components of the currents; cross-canyon components have been mentioned only briefly and spectral analyses, when performed, have not been thoroughly interpreted.

II. EQUIPMENT AND OBSERVATIONAL PROCEDURES

A. CURRENT MEASURING SYSTEMS

1. Geodyne A-100 Current Meter

The Woods Hole Model A-100 Current Meter, manufactured by E.G.& G., Inc. (formerly Geodyne Corporation) in Waltham, Massachusetts, is a self-contained digital recording instrument measuring current direction and speed in the range from below 0.05 knots (2.6 cm/sec) to 5 knots (257 cm/sec) at depths to 6,000 m.

All data are recorded on 16-mm photographic film. The power required is provided by a special 6-volt battery pack, and the record consists of 100 ft of film which permits 5,000 sets of rotor speed, vane, and compass direction readings. The current speed sensor is a Savonius rotor; the vane, which is part of the direction system, is read digitally along with an internal magnetic compass. The film can either be run continuously for 6.5 days or programmed to record currents intermittently for up to a year.

A segment of the 16-mm film output is shown in Fig. 4. The seven intermittent black streaks on the left of the film, following the first continuous streak, show the orientation of the vane relative to a fixed direction within the instrument. The next seven streaks show the orientation of a compass relative to a fixed direction within the instrument. These streaks are made by points of light, transmitted via optical

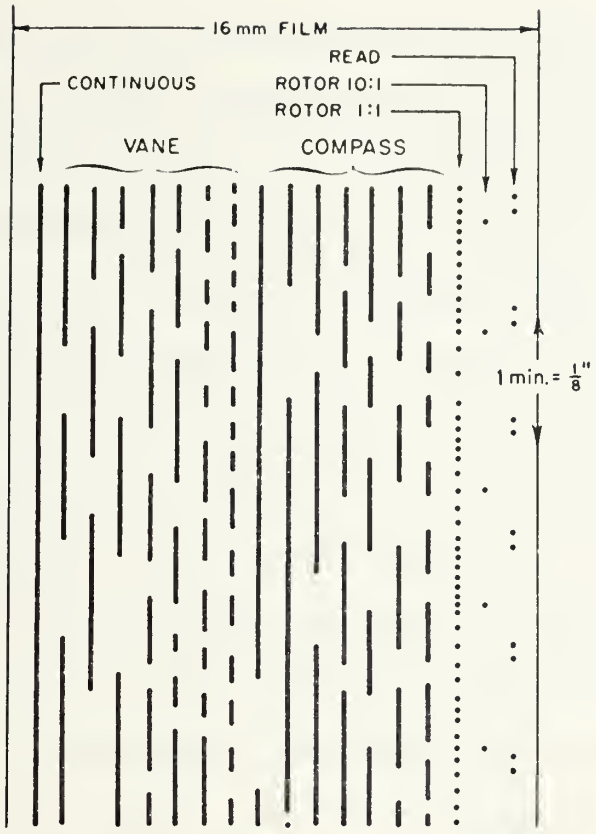


Fig. 4. Format of 16-mm film output. [From Richardson, Stimson, and Wilkins, 1963]

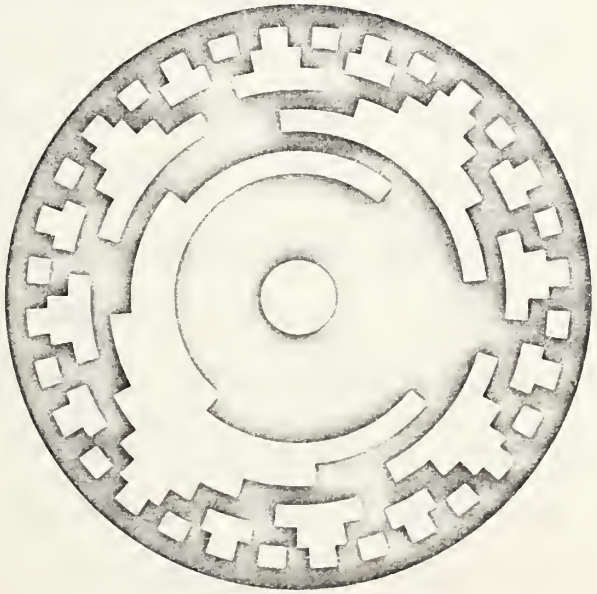


Fig. 5. Encoding disk. [From Richardson, Stimson, and Wilkins, 1963]

fibers, that reach the film as permitted by the encoding disk shown in Fig. 5. The encoding disk is associated with both the vane recording and compass recording systems. Each of the two angles measured by this system can be resolved to 2.5^{o} and the combination of the two angles provided the direction of the current referred to magnetic North.

Each time the Savonius rotor of the meter goes around once, a black dot occurs in the first current channel; ten revolutions causes a dot in the next channel. At times, the rotor is turned so rapidly that the dots in the first channel are too close to be resolved; when this happens the second channel provides current speed information. Timing marks are provided in the last channel [E.G.& G., undated].

2. Hydro Products Model 502 Current Meter

The Model 502 In-Situ Recording System, manufactured by Hydro Products in San Diego, California, is a self-contained instrument package which measures and records current speed, current direction, and temperature. The underwater speed sensor is a Savonius rotor. Water movement past the sensor turns the rotor at an angular rate proportional to the speed of the flow. Ten magnets attached to the rotor close a magnetic reed switch which is in series with a DC voltage source. The output from the sensor is a pulse train whose rate is proportional to the angular rate of the rotor and therefore proportional to the current speed. The rate is measured with a simple rate-meter circuit.

The current direction sensor consists of a microtorque potentiometer and compass. Current direction is measured with reference to magnetic North. The vane of the direction sensor is magnetically connected to the slider of the potentiometer, which is attached to the compass. When the potentiometer is energized by a d.c. voltage, the voltage output on the slider is proportional to its angle of deflection from magnetic North [Hydro Products, undated].

The electronics circuitry, battery, clock timer, and a Rustrak strip chart recorder are contained in an aluminum sphere. The Rustrak recorder incorporates a switching system that allows the three separate parameters to be recorded sequentially as a function of time. The recording cycle is 7.5 min long; speed and temperature are recorded alternately at 4-sec intervals for 1.5 min followed by a 5-min record of speed and direction. The timer starts a new 7.5-min recording cycle every half-hour.

An example of the display obtained is shown in Fig. 6. The three functions are easily identified by the length of the imprint lines of the chart paper.

B. RELEASE MECHANISM

A timed release mechanism manufactured by the Braincon Corporation of Marion, Massachusetts, was used to return the current meter array to the surface. A quartz timer and electronics from a Model 622 release was housed in a Model 422 pressure case. When the timer counts to zero from a preset number, an explosive squib is fired releasing a cocking

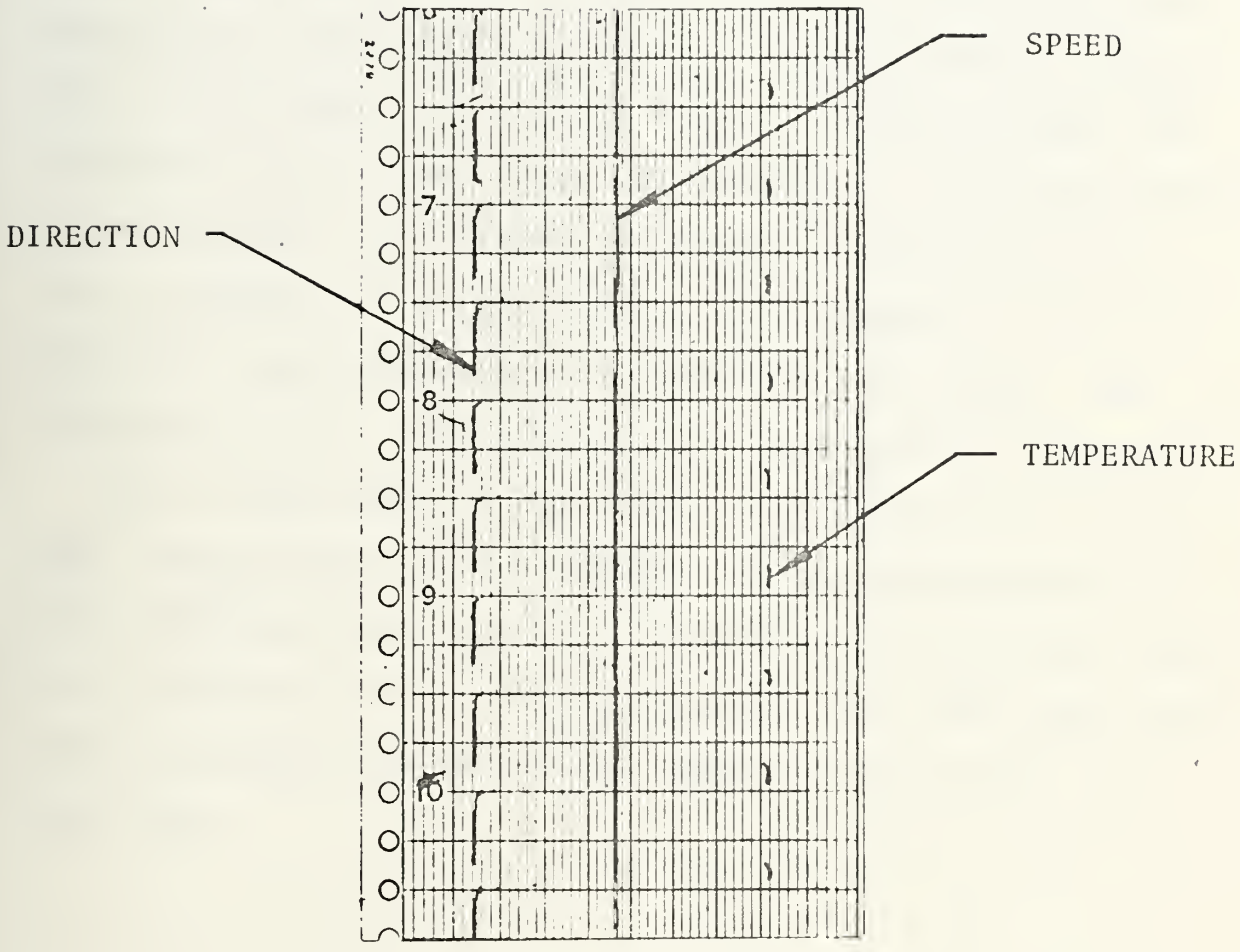


Fig. 6. Format of strip chart output.
[From Hydro Products, undated]

pawl which then allows the mechanism to separate from the anchor.

C. CURRENT METER ARRAY

All instruments used in this investigation were calibrated before deployment, either at the factory or using procedures specified in the operating manual. The array used to deploy the current meters is shown in Fig. 7. Three moorings were attempted but only one array was recovered. The successfully recovered array was deployed in Monterey Submarine Canyon in 485 m of water at position 36^{o} 47.5'N latitude, 121^{o} 54.2'W longitude, approximately 9.6 km WSW of Moss Landing. The statistics of the three moorings are summarized in Table II.

Due to the length of the array, an "anchor-last" deployment was made from the R/V ACANIA. As the emplacement site was approached, the array was streamed behind the ship, buoys first, with the anchor retained aboard. After the emplacement site was passed, the anchor was dropped and the array sank into place.

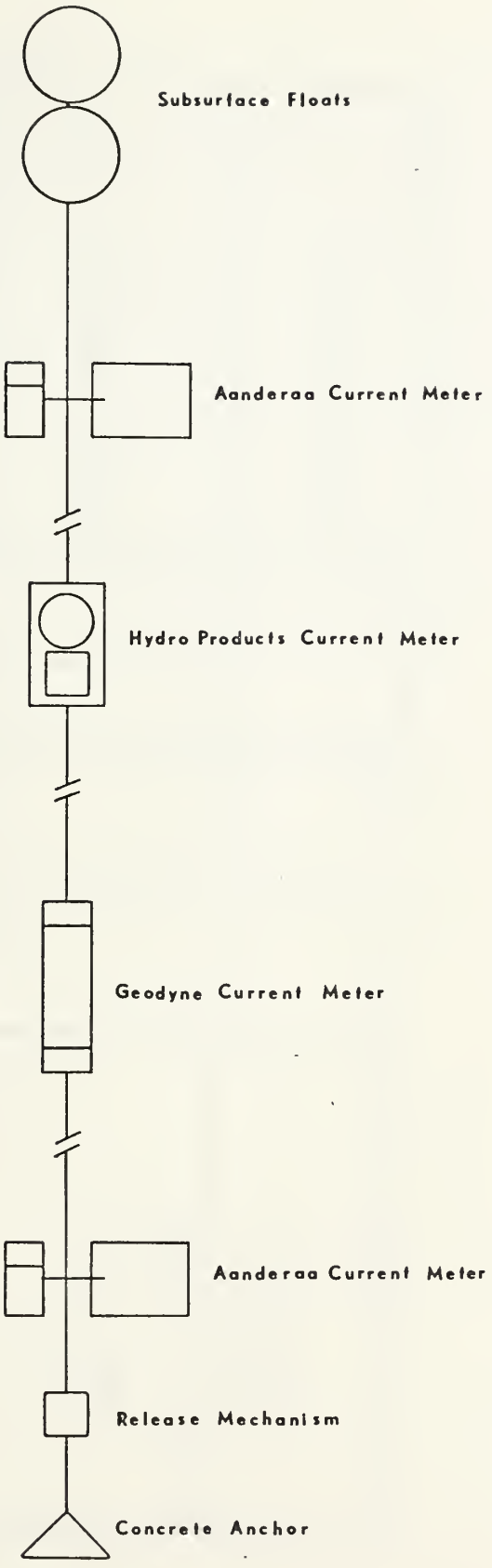


Fig. 7. Current meter array.

Station Location & Depth	Height Above Bottom	Record Length	Remarks
	425 m	0	Pressure case flooded
36° 47.5' N	60 m	371 hr	
121° 54.2' W	30 m	262 hr	Directions for 342 hr
485 m	3 m	0	Electronics malfunction
	707 m	0	
36° 46.0' N	60 m	0	Release Failure
121° 57.8' W	30 m	0	
767 m	3 m	0	
36° 47.5' N	30 m	0	
121° 54.2' W	10 m	0	Release Failure
485 m			

TABLE II. Mooring Statistics

III. DATA ANALYSIS

A. SAMPLING RATES AND DIGITIZING PROCEDURES

The Geodyne A-100 current meter was programmed to sample speed and direction for 50 sec at 5-min intervals. The developing and printing of the current meter film was handled by E.G.& G., Environmental Equipment Division. An automatic film reader was then used to convert the Grey binary code on the film into digital form. This output was subsequently transferred to punched computer cards.

A characteristic of the computer program associated with the automatic film reader is that if the current meter records a speed below that designated as the threshold of sensitivity for the instrument an "implied zero" is printed. Since it is unlikely that currents in the canyon are really zero for any significant length of time, a value of 1.54 cm/sec, approximately half the threshold speed, was substituted for the implied zero value. This accounts for the apparent "floor" seen in the speed versus time graphs of the 30 m above-bottom record.

When employing the Hydro Products Model 502 current meter one must choose between a continuous record with a 7-day data storage capacity, or a 30-min sampling interval with a 30-day recording life. Since a long time series was desired, the 30-min sampling interval was selected. This rate was frequent enough to describe long period variations, but may have been

insufficient to fully describe high frequency variations of speed and direction. The resulting aliasing problem is discussed later in this section.

The analog strip chart data was digitized at 30-min intervals using calibration plates supplied with the instrument and the resulting numbers punched onto computer cards.

B. ELEMENTARY STATISTICS

Program SUBMARINE CANYON (Appendix A), an extensive modification of a program written by Dooley [1968], was used to compute the basic statistics of the current meter data, as listed below.

The outputs from SUBMARINE CANYON include:

(1) hourly means,

(2) daily means, medians, modes, and frequency distributions, and

(3) time series means, medians, modes, standard deviations, and direction histograms.

Average speed is defined as a simple arithmetic mean. For N speed observations, V_i, the average is defined as:

$$\bar{V} = \frac{1}{N} \sum_{i=1}^{N} V_i \qquad \text{average speed}$$

However, to give more physical meaning to an average velocity a vector average, obtained by using the mean north and east components as shown below, is used to define an average direction:

$$\bar{V}_e = \frac{1}{N} \sum_{i=1}^{N} (V_i \sin \theta_i) \qquad \text{average east component}$$

$$\bar{V}_n = \frac{1}{N} \sum_{i=1}^{N} (V_i \cos \theta_i) \qquad \text{average north component}$$

$$\bar{\theta} = \arctan \left(\frac{\bar{V}_e}{\bar{V}_n}\right) \qquad \text{average direction}$$

where θ_i is the i^{th} direction observation.

C. GRAPHIC DISPLAYS OF CURRENT METER DATA

1. Histograms

The direction histograms (Fig. 8a and 8b) are also an output of SUBMARINE CANYON. The range of directions is divided into 10^o intervals and the frequency of occurrence of directions within each interval is computed and plotted. The most common values of direction and the variances about them are readily determined by examination of the histograms.

It is physically misleading, however, to interpret the independent modal values of direction as a description of an average velocity vector; the directions plotted do not use coincident current speeds as weighting factors and therefore do not accumulate to a vector average. Vector scatter diagrams are more indicative of flow direction.

2. Scatter Diagrams

Scatter diagrams (Fig. 9 and 10) are used to complement the histograms. These polar plots of the current vectors clearly associate speeds with directions and give a more precise physical meaning to the bi-modal character of the flow suggested by the direction histograms. However, because large vectors obscure small ones, this type of presentation is

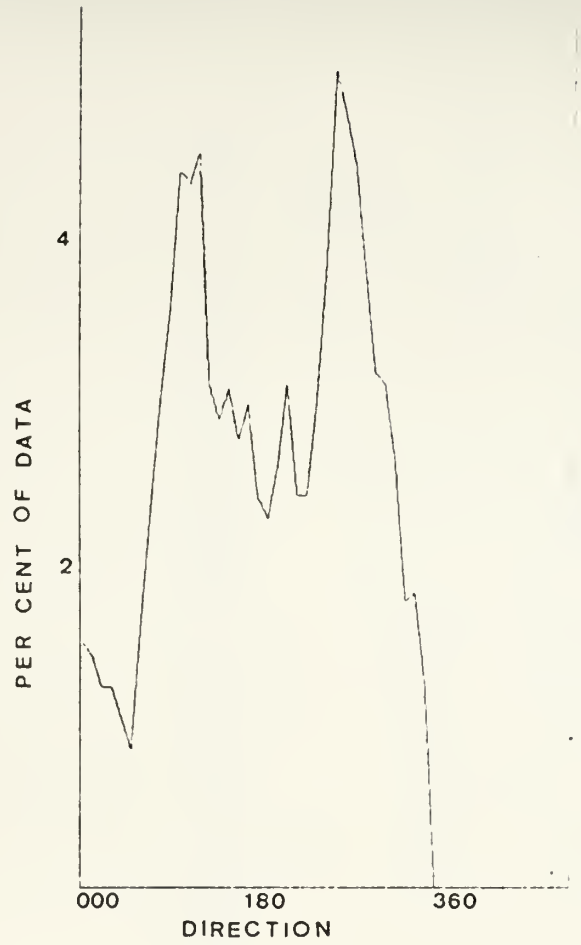


Fig. 8a. Direction Histogram, 30 m above bottom

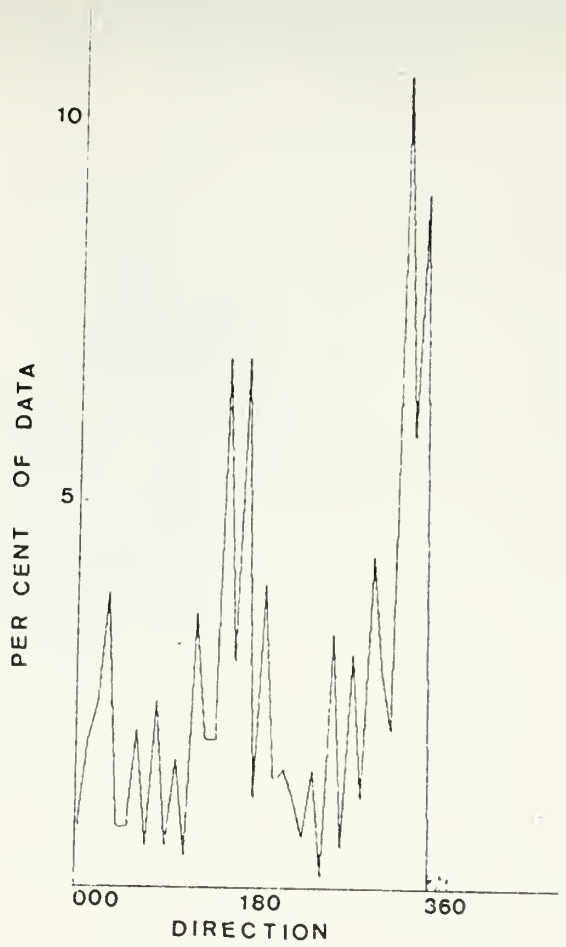


Fig. 8b. Direction Histogram, 60 m above bottom

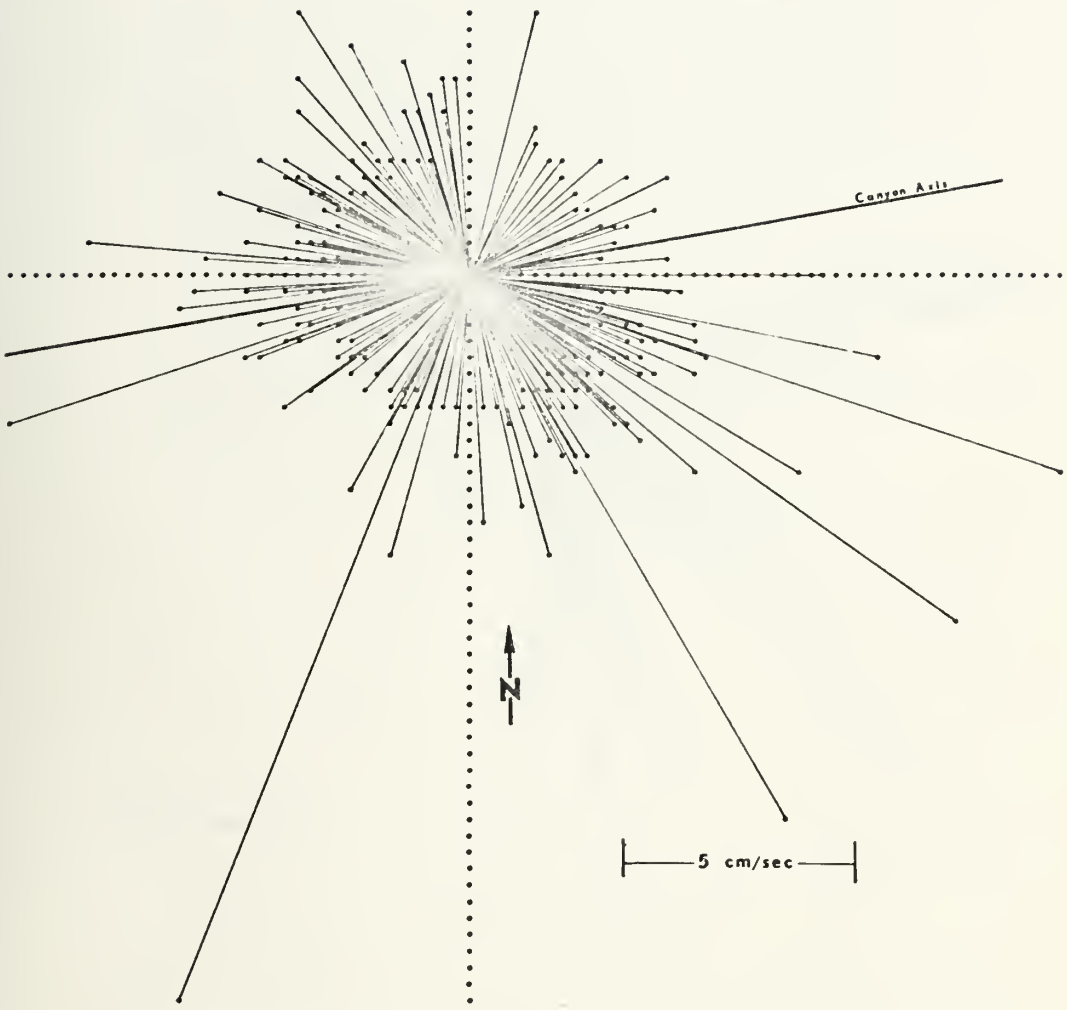


Fig. 9. Scatter Diagram, 30 m above bottom.

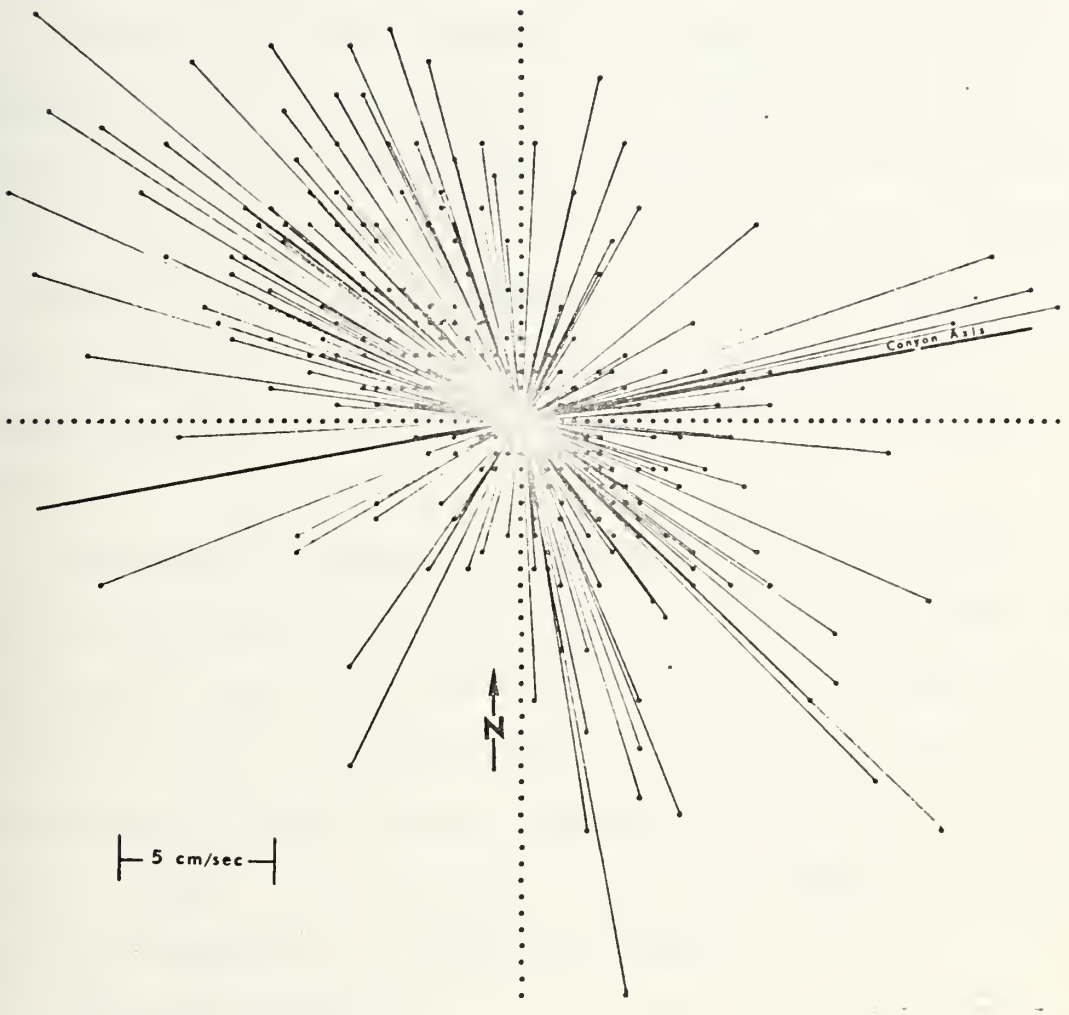


Fig. 10. Scatter Diagram, 60 m above bottom.

also imperfect. Progressive vector diagrams must be examined to obtain some measure of the net flow.

3. Progressive Vector Diagrams

Vector displacement, or progressive vector diagrams (Fig. 11 through 14) are convenient methods of graphically representing time series current meter observations. They are useful for quickly portraying the mean flow and the general character of low frequency--particularly rotary--changes, and also put high frequency changes into perspective as to magnitude [Webster, 1964a]. The diagram is constructed by computing the vector sum of displacements over given time intervals.

Although the progressive vector diagram resembles a particle trajectory, it is unwise to think of it as such. Only in the special case where the field of motion is independent of position over the spatial scale of the summed vectors would the progressive vector diagram represent a particle trajectory [Webster, 1964b]. It is unlikely that this condition exists within the confines of a submarine canyon.

4. Composite Drawings

Current speeds and directions were plotted versus time in 24-hr increments for the entire time series. In these graphs (Fig. 15 through 30), which were generated by program COMPOSITE DRAW (Appendix B), the general character of the fluctuations of the parameters may be ascertained. The directions 60 m above bottom never go through 360^{o}, so direction rotations cannot be seen. This is due to the sampling procedure

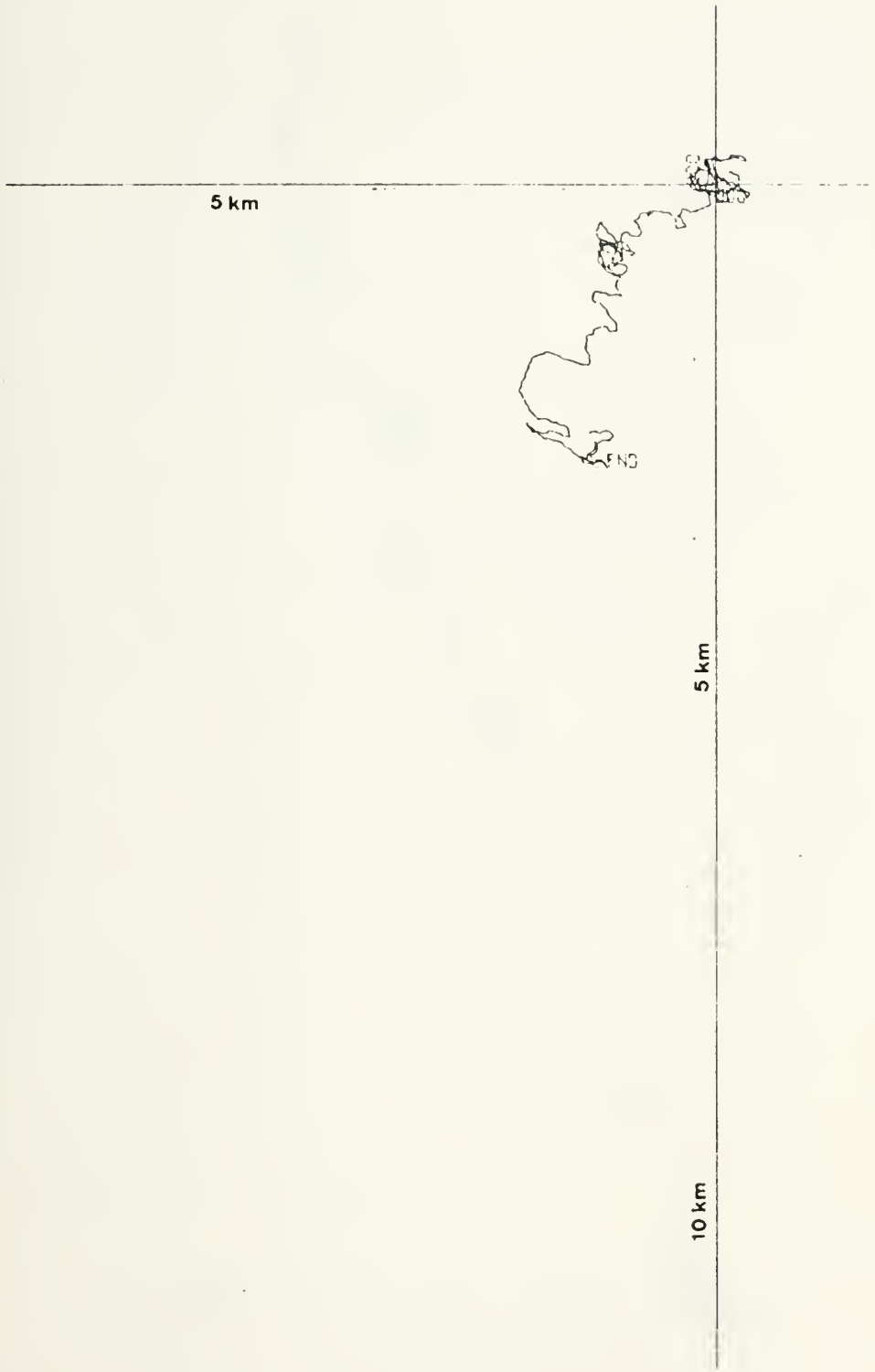


Fig. 11. Progressive Vector Diagram, 30 m above bottom.

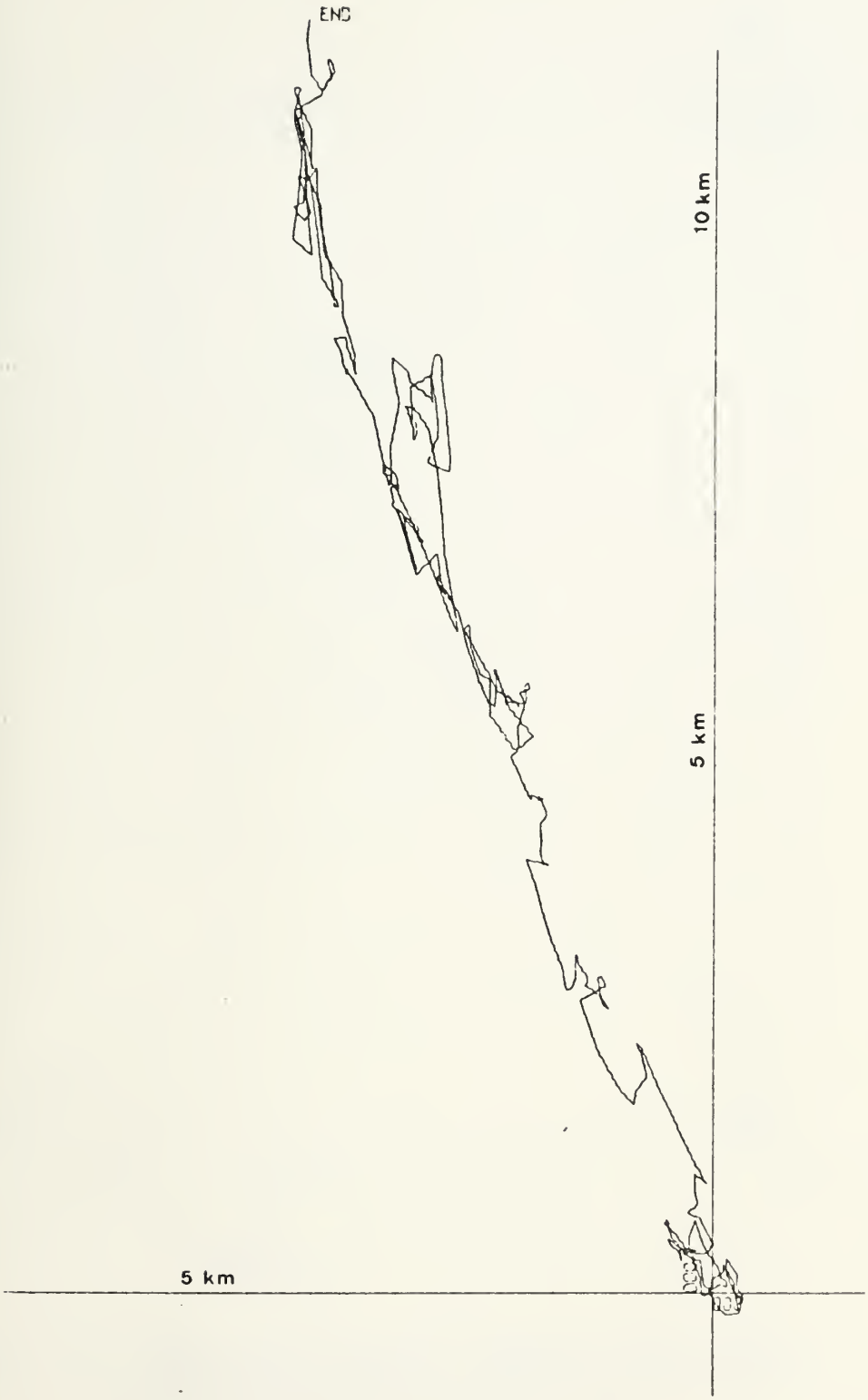


Fig. 12. Progressive Vector Diagram, 60 m above bottom.

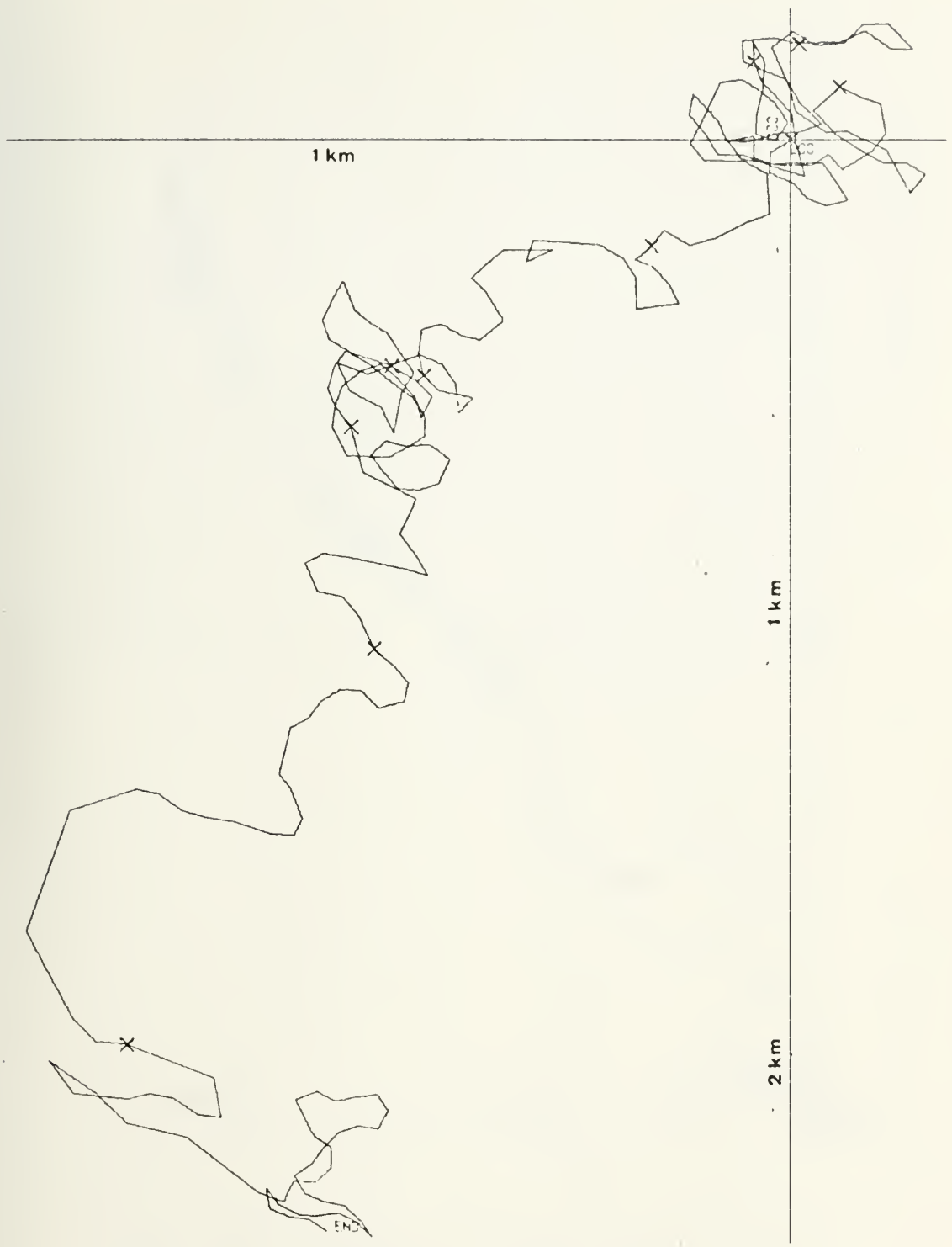


Fig. 13. Progressive Vector Diagram, 30 m above bottom (expanded scale). Successive 24-hr periods marked by "X".

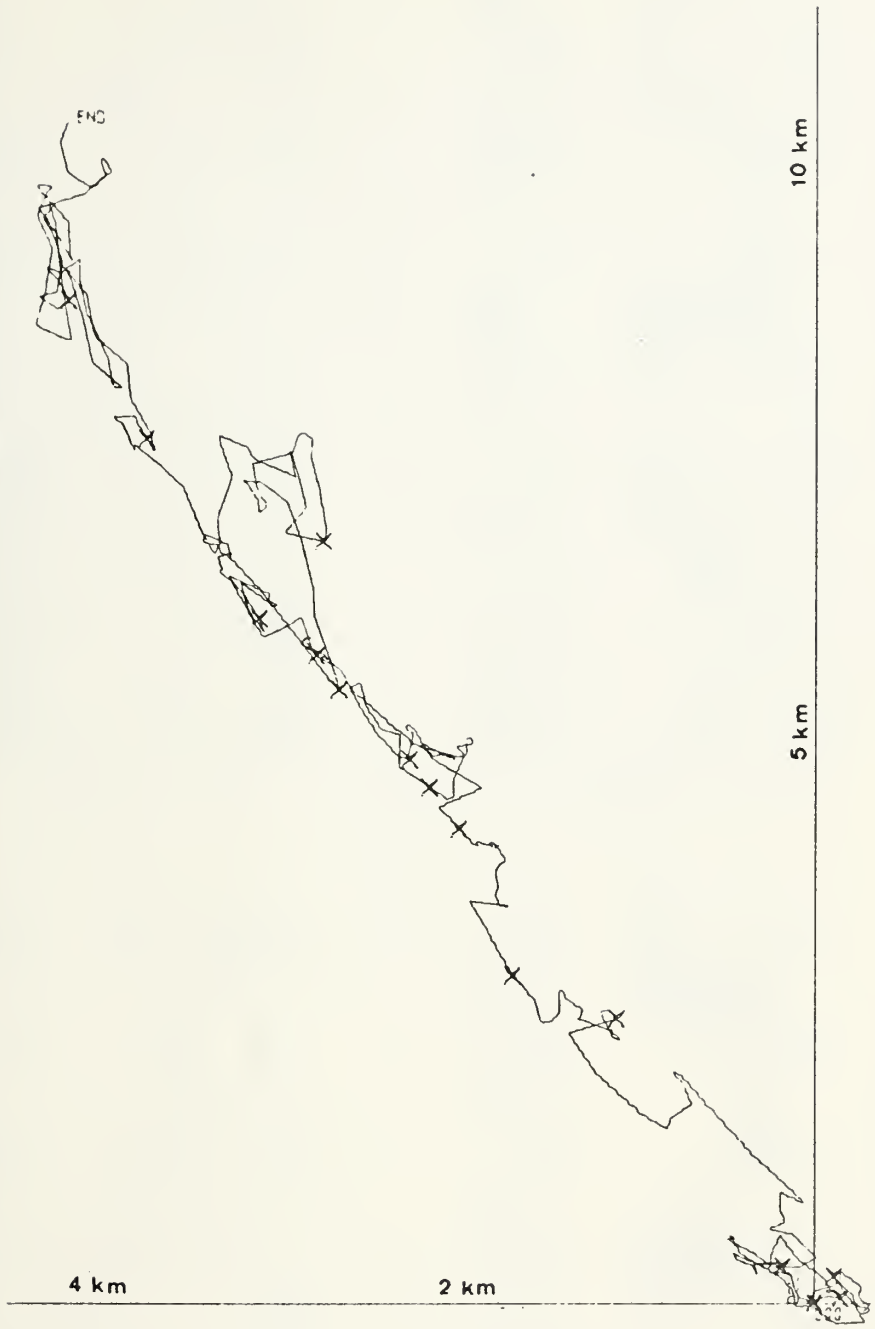


Fig. 14. Progressive Vector Diagram, 60 m above bottom (expanded scale). Successive 24-hr periods marked by "X".

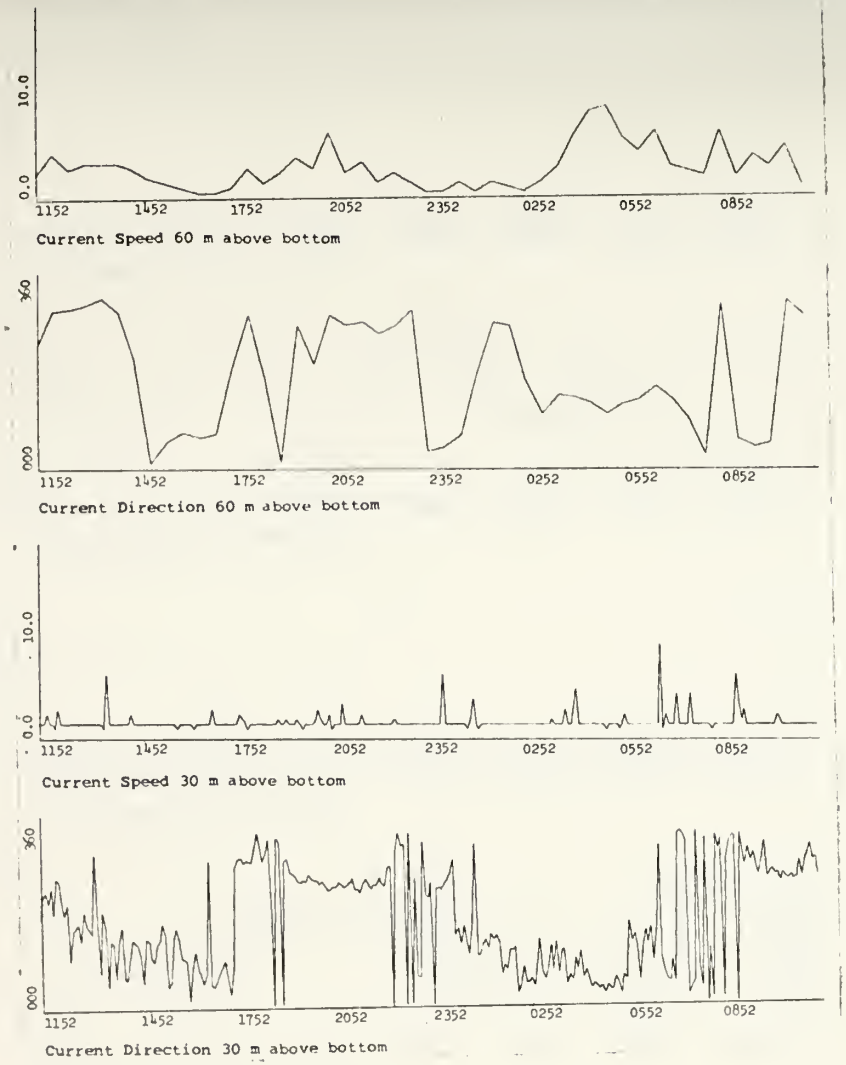


Fig. 15. Composite Drawings, 29 Oct - 30 Oct

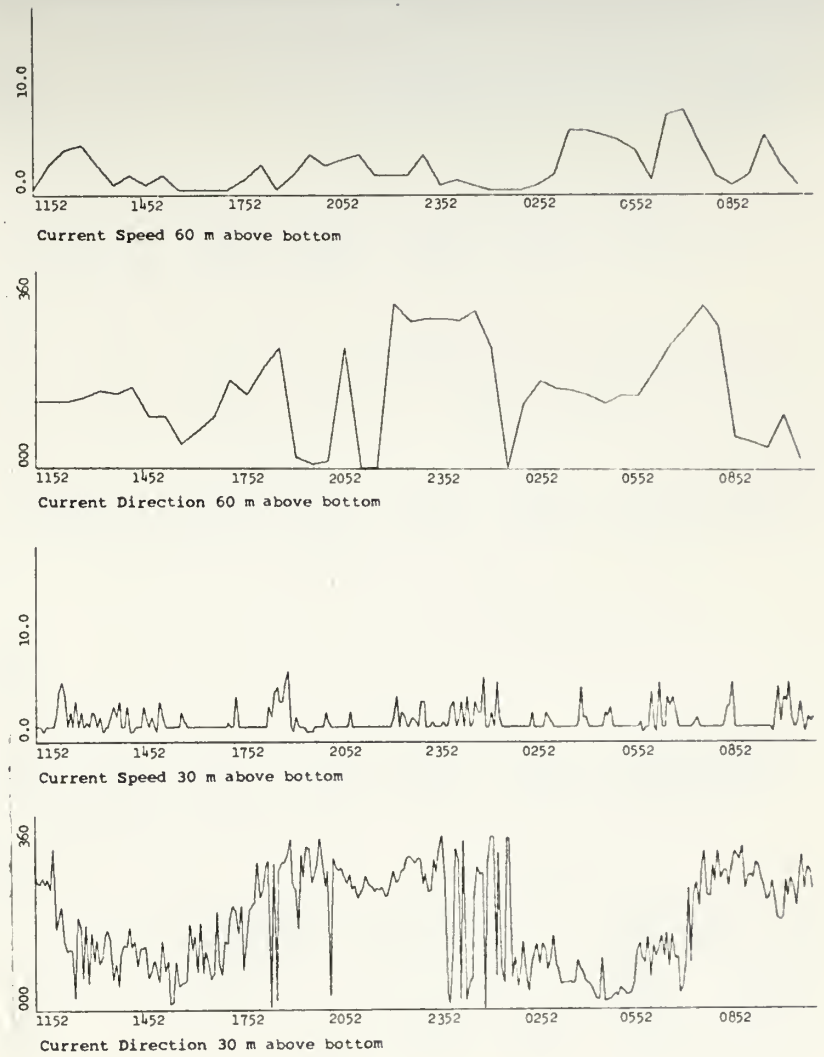
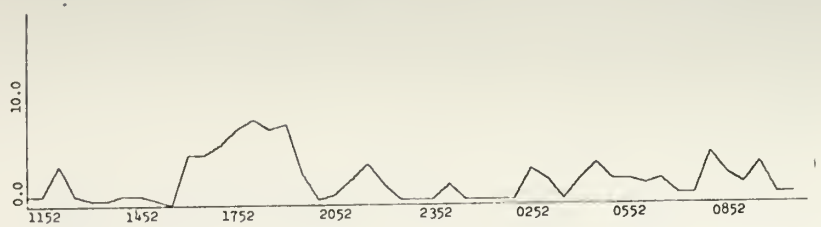


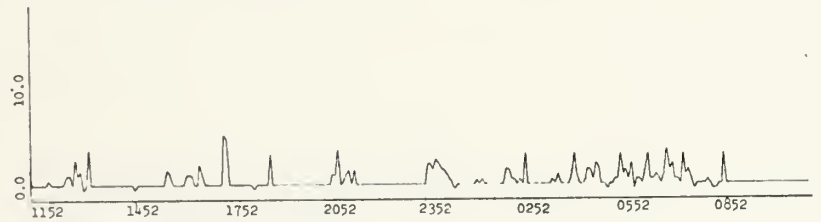
Fig. 16. Composite Drawings, 30 Oct - 31 Oct

(Fig. 15-30, speeds in cm/sec; time is PDT)

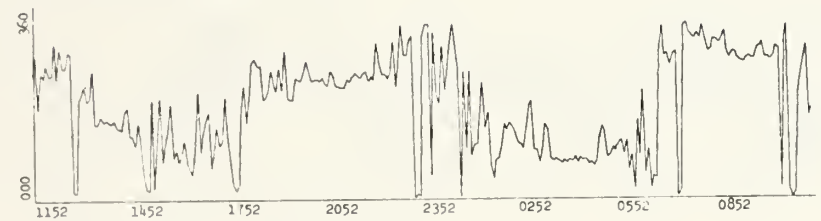


Current Speed 60 m above bottom

Current Direction 60 m above bottom

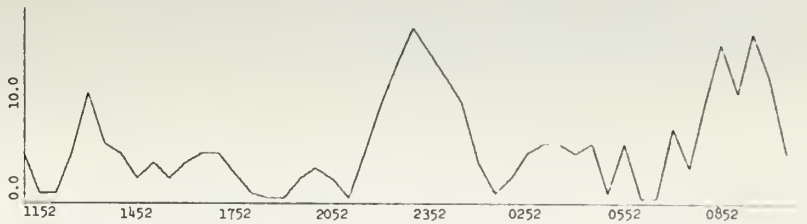


Current Speed 30 m above bottom

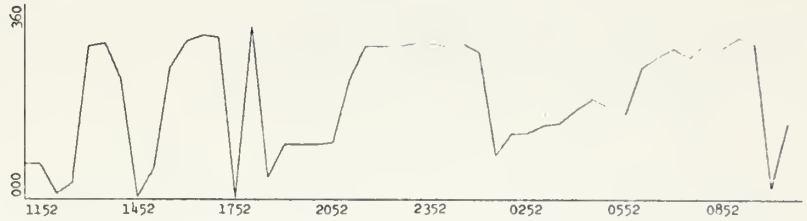


Current Direction 30 m above bottom

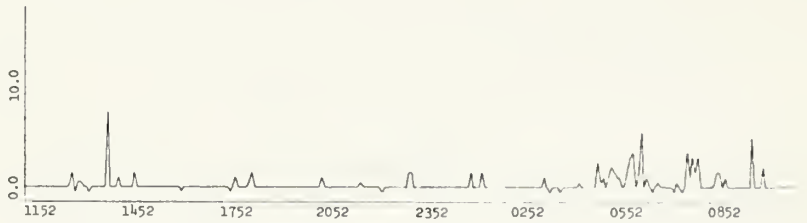
Fig. 17. Composite Drawings, 31 Oct - 1 Nov



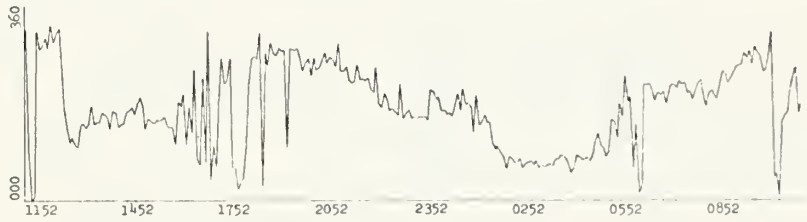
Current Speed 60 m above bottom



Current Direction 60 m above bottom



Current Speed 30 m above bottom



Current Direction 30 m above bottom

Fig. 18. Composite Drawings, 1 Nov - 2 Nov

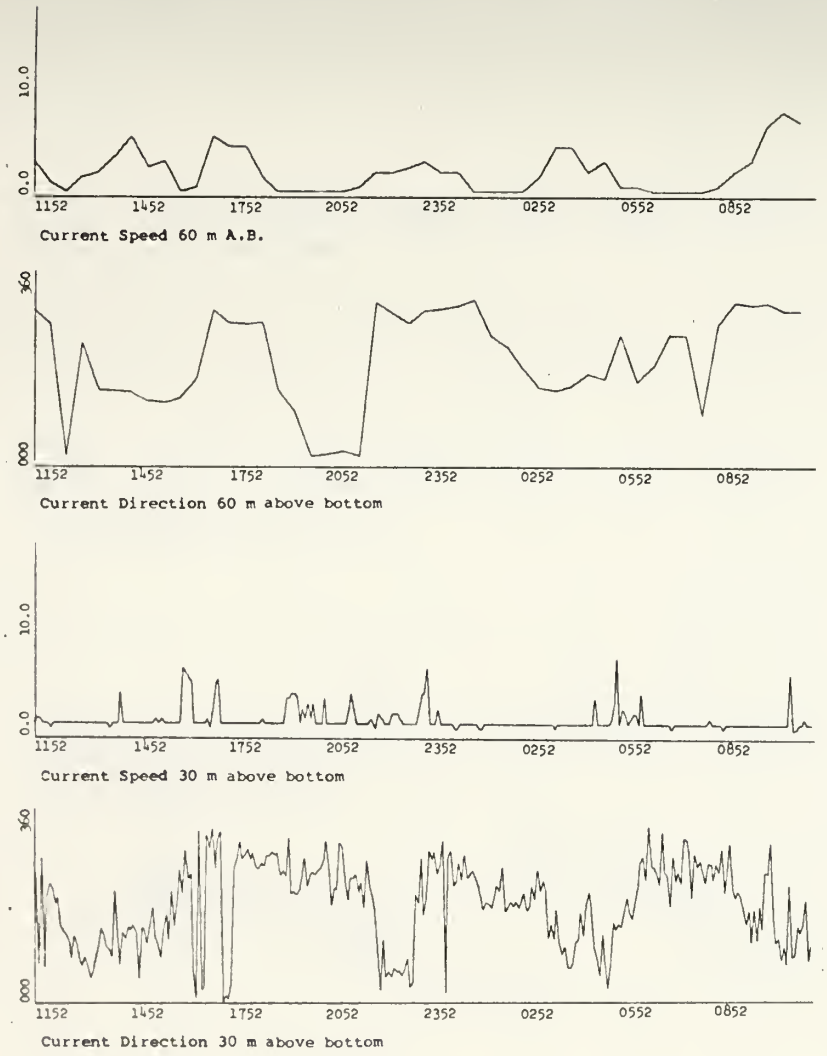


Fig. 19. Composite Drawings, 2 Nov - 3 Nov

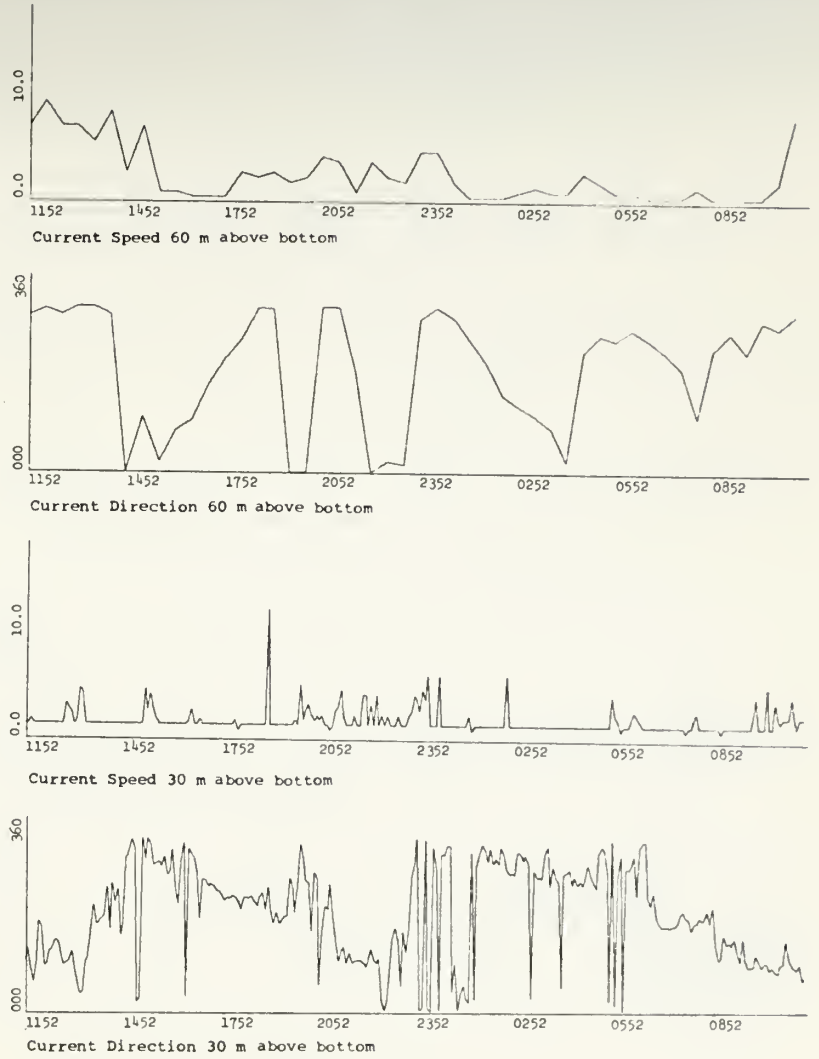


Fig. 20. Composite Drawings, 3 Nov - 4 Nov

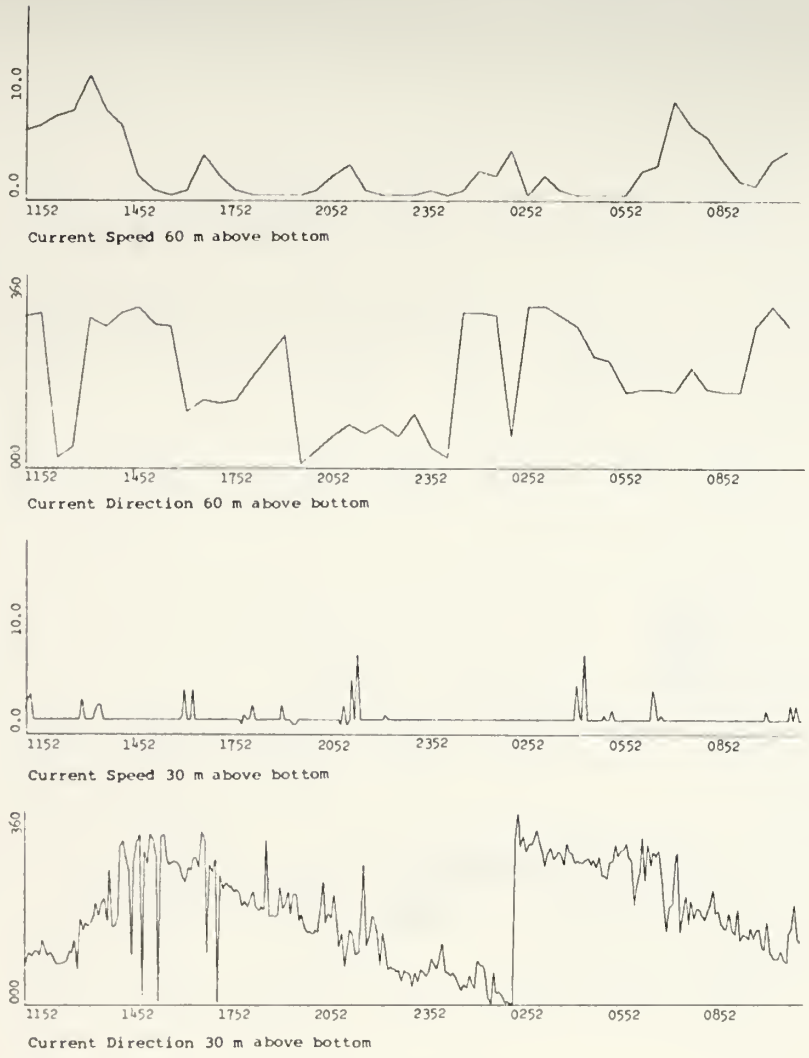


Fig. 21. Composite Drawings, 4 Nov - 5 Nov

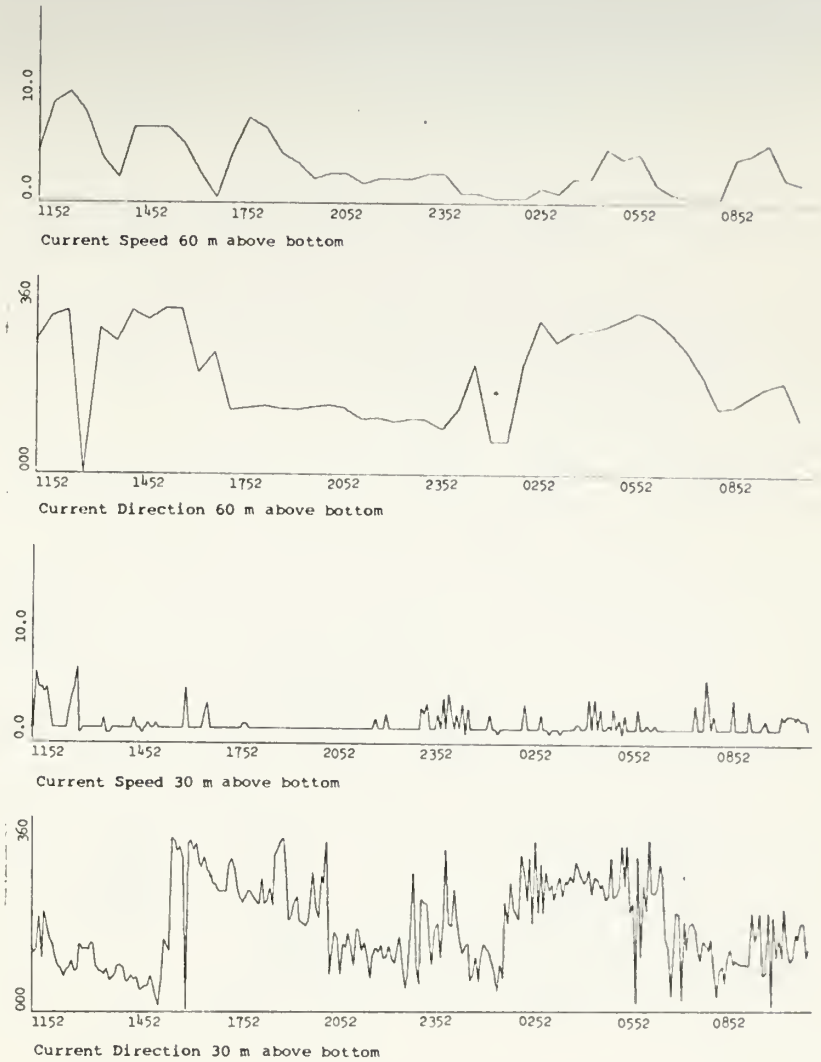


Fig. 22. Composite Drawings, 5 Nov - 6 Nov

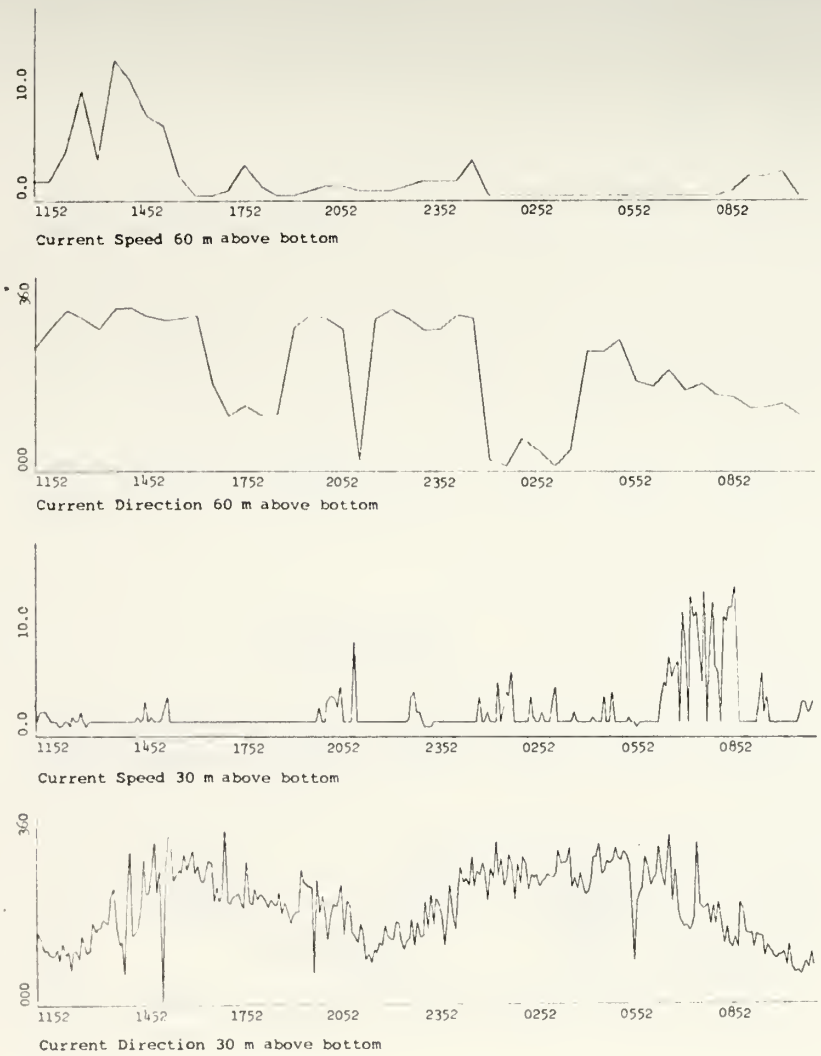


Fig. 23. Composite Drawings, 6 Nov - 7 Nov

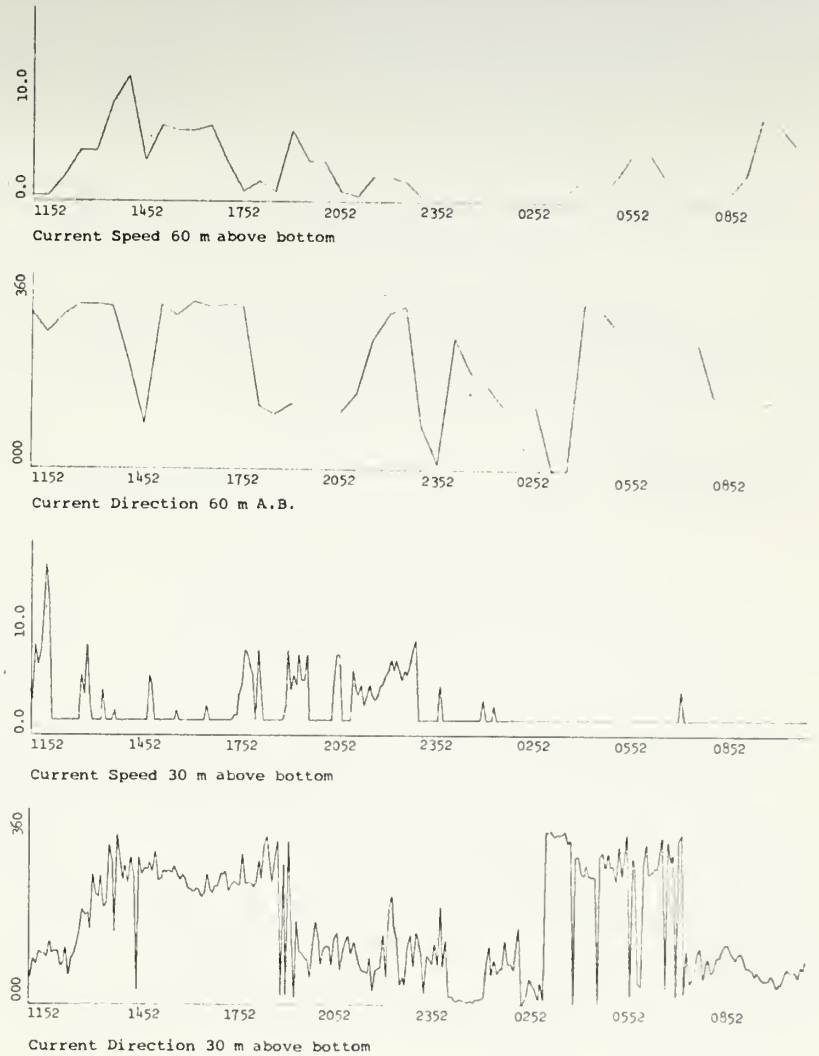
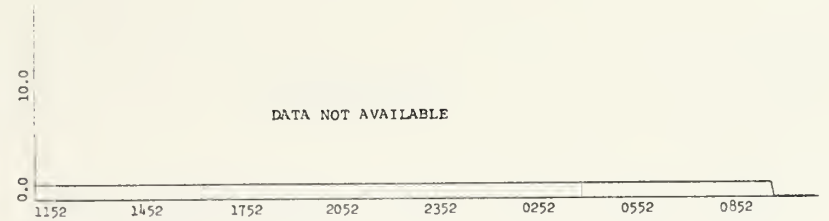


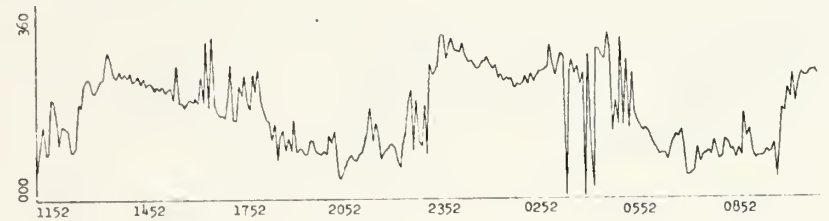
Fig. 24. Composite Drawings, 7 Nov - 8 Nov

Current Speed 60 m above bottom

Current Direction 60 m above bottom

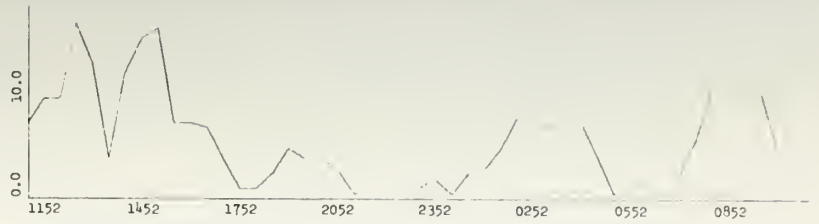


Current Speed 30 m above bottom

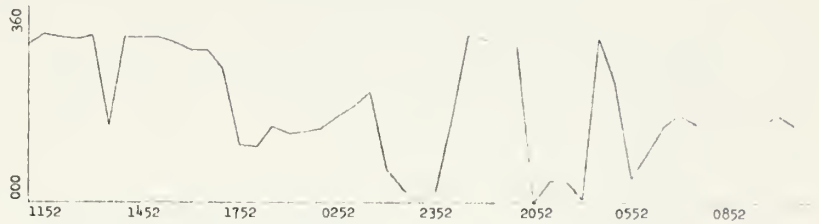


Current Direction 30 m above bottom

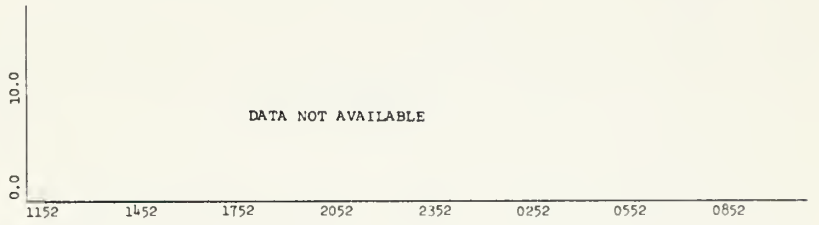
Fig. 25. Composite Drawings, 8 Nov - 9 Nov



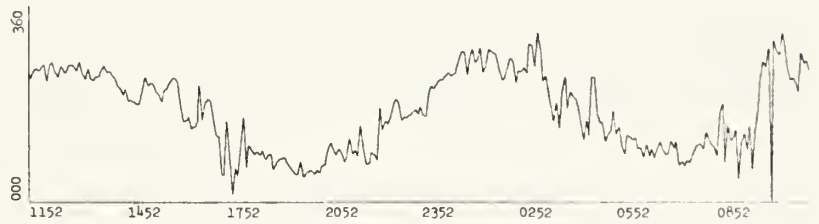
Current Speed 60 m above bottom



Current Direction 60 m above bottom



Current Speed 30 m above bottom



Current Direction 30 m above bottom

Fig. 26. Composite Drawings, 9 Nov - 10 Nov

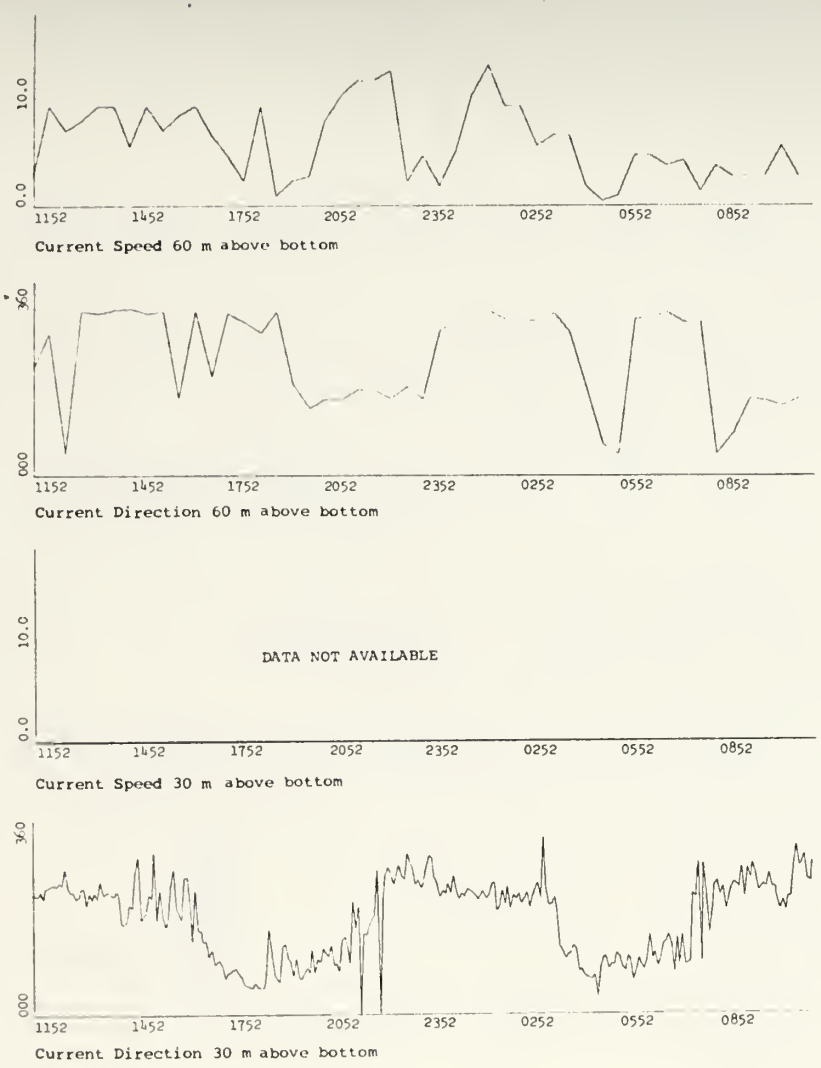


Fig. 27. Composite Drawing, 10 Nov - 11 Nov

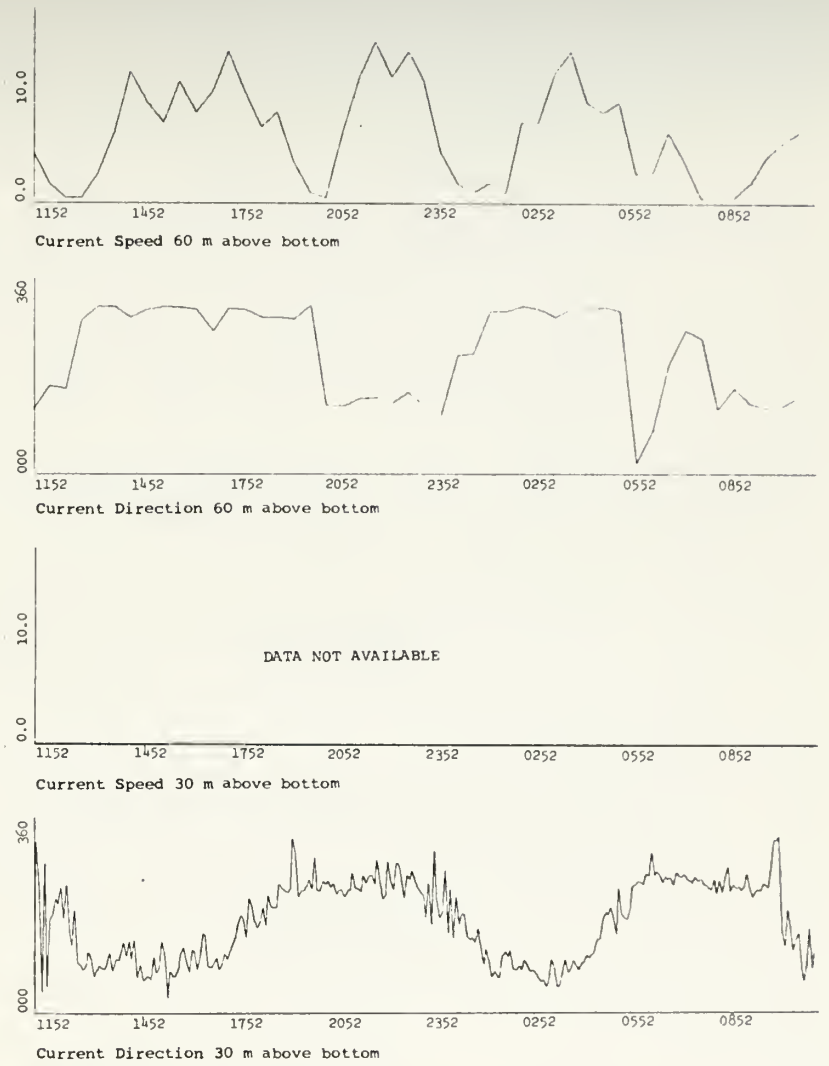
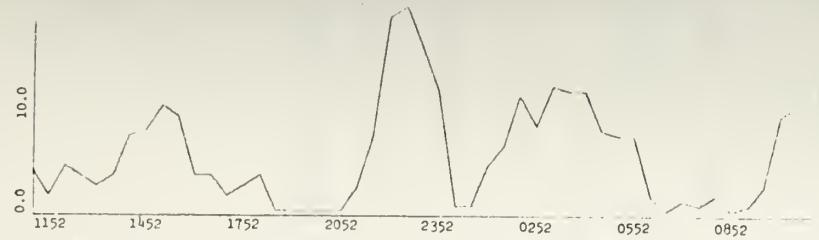
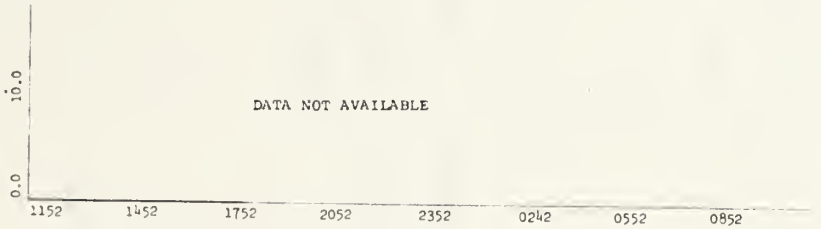


Fig. 28. Composite Drawing, 11 Nov - 12 Nov

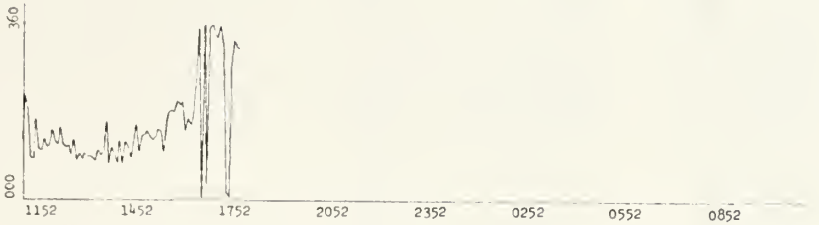


Current Speed 60 m above bottom

Current Direction 60 m above bottom

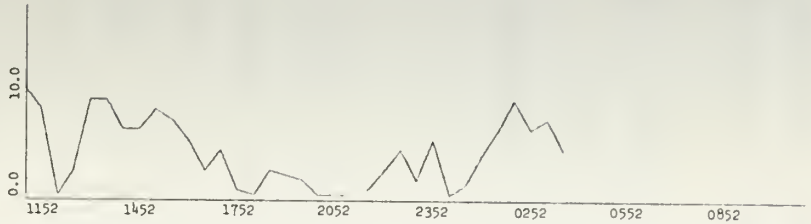


Current Speed 30 m above bottom



Current Direction 30 m above bottom

Fig. 29. Composite Drawings, 12 Nov - 13 Nov



Current Speed 60 m above bottom

Current Direction 60 m above bottom

DATA NOT AVAILABLE

Current Speed 30 m above bottom

DATA NOT AVAILABLE

Current Direction 30 m above bottom

Fig. 30. Composite Drawings, 13 Nov - 14 Nov

employed: values were picked off the strip chart by hand and points of cross-over were avoided.

D. ALIASING

The Hydro Products Model 502 current meter, with a 30-min sampling interval, has a cutoff frequency, defined by:

$$f_c = \frac{1}{2h}, \text{ where } h = \text{sampling interval},$$

of one cycle per hour. Therefore, although useful for resolving tidally-generated fluctuations, this sampling rate is useless for defining frequencies higher than 1 cycle/hr. Furthermore, the lower frequencies will be contaminated by high frequencies if the latter are present in the signal before sampling.

E. HIGHER ORDER STATISTICS

Autospectra and cross-spectra were calculated for the two time series using BMD 02T, a computer program from the Health Sciences Computing Facility at UCLA.

A constant time interval of 30.0 min was used; 50 lags, equalling 7.2% of the data, were chosen to provide adequate resolution in the power spectral estimates, and all data were detrended to remove any frequency components whose periods were longer than the record length.

IV. DISCUSSION

The discussion which follows deals with the recorded data on two levels: (i) the apparent characteristics, which describe the general character of the current flow and are determined by examination of the various graphic presentations; (ii) the spectral characteristics, which describe the variability of the time series and the character of their periodic and irregular oscillations.

A. APPARENT CHARACTERISTICS

Very generally, the currents observed during the course of this investigation were similar in character to those observed and reported on by previous investigators. Current directions oscillated up and down or across the canyon and speeds (the scalar magnitude of current vectors) were variable with recorded maxima of the order of 20 cm/sec.

Table III shows a summary of the elementary statistics from both current meter records. The mean speed for each record was significantly lower than those reported by earlier investigators; speed variations, instead of oscillating smoothly, appeared as a series of peaks or spikes, particularly in the case of the record 30 m above-bottom (Fig. 15 through 24). The volume transport (in cubic meters/hour) calculated in program VECTOR DRAW (Appendix C) was also significantly lower than that reported by other investigators, and is particularly interesting in that the rate of flow

	30 m Above Bottom	60 m Above Bottom
Mean scalar speed	2.01 cm/sec	4.19 cm/sec
Mean up-canyon component	0.309 cm/sec	0.003 cm/sec
Mean cross-canyon component	0.131 cm/sec	0.978 cm/sec
Mean velocity	0.336 cm/sec	0.978 cm/sec
Maximum scalar speed	17.50 cm/sec	21.62 cm/sec
Maximum up-canyon component	6.36 cm/sec	9.56 cm/sec
Maximum cross-canyon component	8.67 cm/sec	18.01 cm/sec
σ (scalar speeds)	1.41 cm/sec	3.95 cm/sec
σ (up-canyon)	0.945 cm/sec	0.039 cm/sec
σ (cross-canyon)	0.985 cm/sec	0.073 cm/sec
Vector mean direction	193.16^{o}	217.89^{o}
Volume transport/hr (per square meter)	12.08 m^3/hr	36.97 m^3/hr

TABLE III. Elementary Current Statistics

increases with distance above bottom. Although this is the condition commonly found in the open ocean, it is contrary to the results, presented by other investigators, of current studies in submarine canyons.

Current directions oscillated fairly smoothly with a discernible period of about 12 hr, with higher-frequency oscillations superimposed (Fig. 15 through 30). The frequencies of oscillation of the scalar speeds are sometimes doubled due to the rectification that is inherent with this type of plot. The direction histograms (Fig. 8a and 8b) show the characteristic bi-modal shape expected of a record from within the narrow confines of the canyon.

The canyon axis at the investigation site is oriented 080^{o} - 260^{o}. The dominant modes of the direction histogram from the 30 m above-bottom record (Fig. 8a) indicate that the flow is predominantly along the canyon axis at that depth. The direction histogram from the 60 m above-bottom record (Fig. 8b), however, shows dominant modes perpendicular to the canyon axis indicating that the flow has a strong cross-canyon component. This is confirmed by the scatter diagram for this level (Fig. 14). This cross-canyon flow obviously cannot continue for any great distance because of the canyon walls; local direction deviations due to topography must therefore occur. The causes of this cross-canyon flow are speculative. As mentioned earlier, Shepard, Marshall and McLoughlin [1974a] have suggested a relation between the occurrence of cross-canyon winds and cross-canyon current surges, and noted a

repetition cycle that is apparently tidally influenced. In deep canyons the cross-canyon flow may be caused by local topographic effects, or by semi-permanent eddy structures along the canyon walls. It may also be due to intrusion into the canyon of motions along the continental slope.

The direction of net transport can be inferred from the progressive vector diagrams (Fig. 9 and 10) by noting the apparent net direction of particle movement. This direction is 220° for the record 30 m above bottom and 330° for the record 60 m above bottom. These diagrams are drawn to the same length scale so that relative flows may be seen. The expanded diagrams (Fig. 11 and 12) fill the printing frame and more clearly show the details of the flow, but have different scales. In these diagrams successive 24-hr periods are marked with an "X".

The composite drawings of current direction versus time (Fig. 15 through 30) clearly show oscillatory changes of direction with a dominant period of approximately 12 hr. This characteristic is particularly apparent in the record 30 m above bottom, due to the higher sampling rate employed there, but can also be seen in the record 60 m above bottom. There is a phase difference between the two levels of about 4 hr. It is interesting that the 4-hr time period corresponds to 90° of tidal rotation. It is not clear, however, that the observed 90° (approximate) angular displacement between the two levels has its cause in this factor. The vertical coherence of these oscillations will be discussed in the section on spectral characteristics.

Speed oscillations are much less clearly defined in both records, but peaks tend to occur every 5 to 6 hr, which is characteristic of a reversing current with a 10- to 12-hr period. A relationship between peak speeds and direction is not evident in these graphs, but may clearly be seen in the graphs of up-canyon and cross-canyon components versus time (Fig. 31 and 32).

B. SPECTRAL CHARACTERISTICS

Power spectral estimates of the two time series were generated to identify the frequencies which contribute to the overall variability of the series. Spectral estimates are presented in a linear plot against frequency to avoid the area distortion of the common logarithmic presentation. Power spectra were computed for (i) up-canyon velocity 60 m above bottom (Fig. 33); (ii) cross-canyon velocity 60 m above bottom (Fig. 34); (iii) up-canyon velocity 30 m above bottom (Fig. 35); (iv) cross-canyon velocity 30 m above bottom (Fig. 36). Aperiodic fluctuations and surges, possibly due to solitary internal waves or eddies from the California Current, are reflected in the very low frequency portions of the spectra.

The phase, coherence, and cross-spectral estimates were computed between: (i) 60 m up-canyon velocity and 30 m up-canyon velocity; (ii) 60 m cross-canyon velocity and 30 m cross-canyon velocity; (iii) 60 m cross-canyon velocity and 30 m up-canyon velocity.

Fig. 31. Directional Components versus Time, 30 m above bottom.

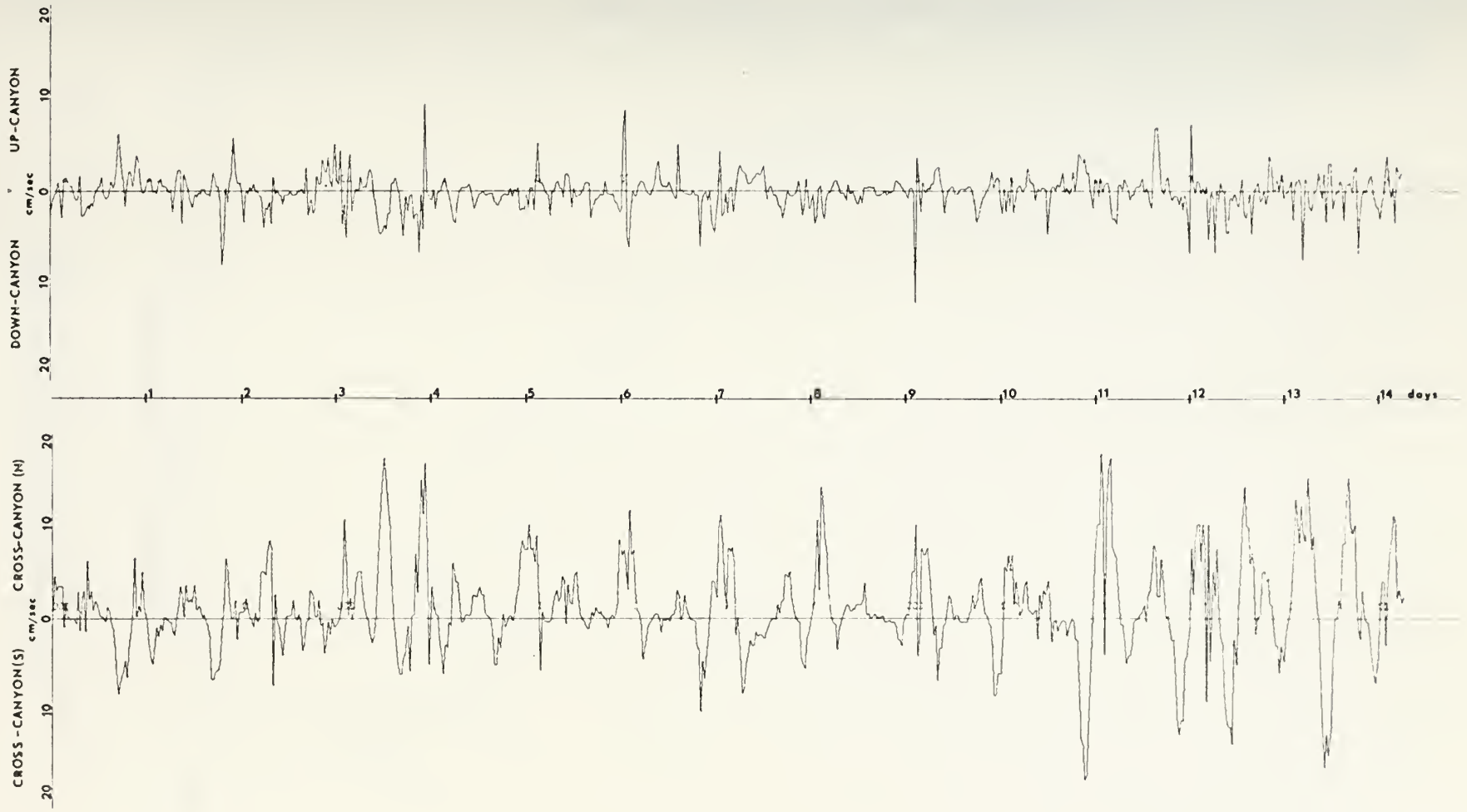


Fig. 32. Directional Components versus Time, 60 m above bottom.

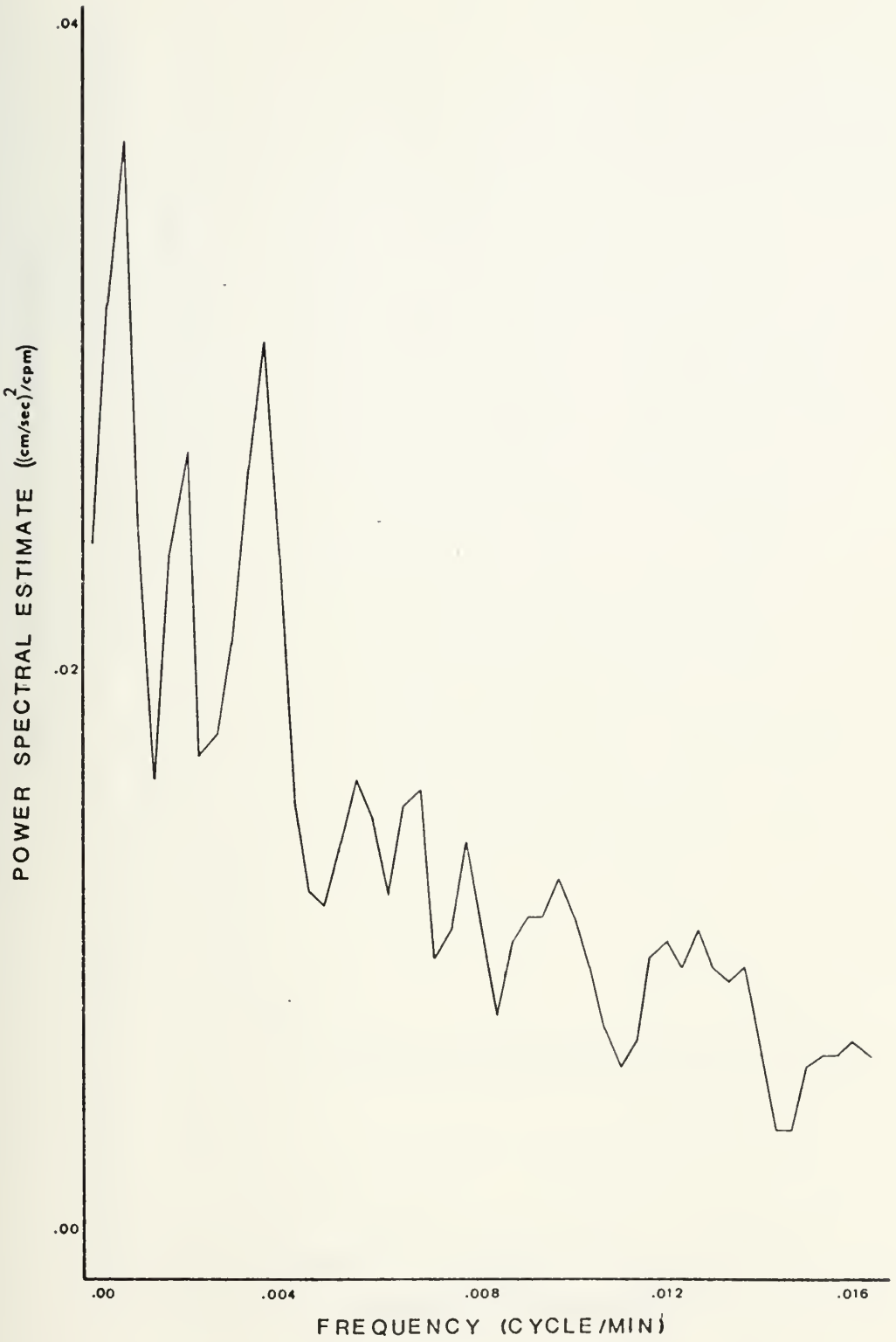


Fig. 33. Power Spectral Estimate, Up-Canyon Component 60 m above bottom

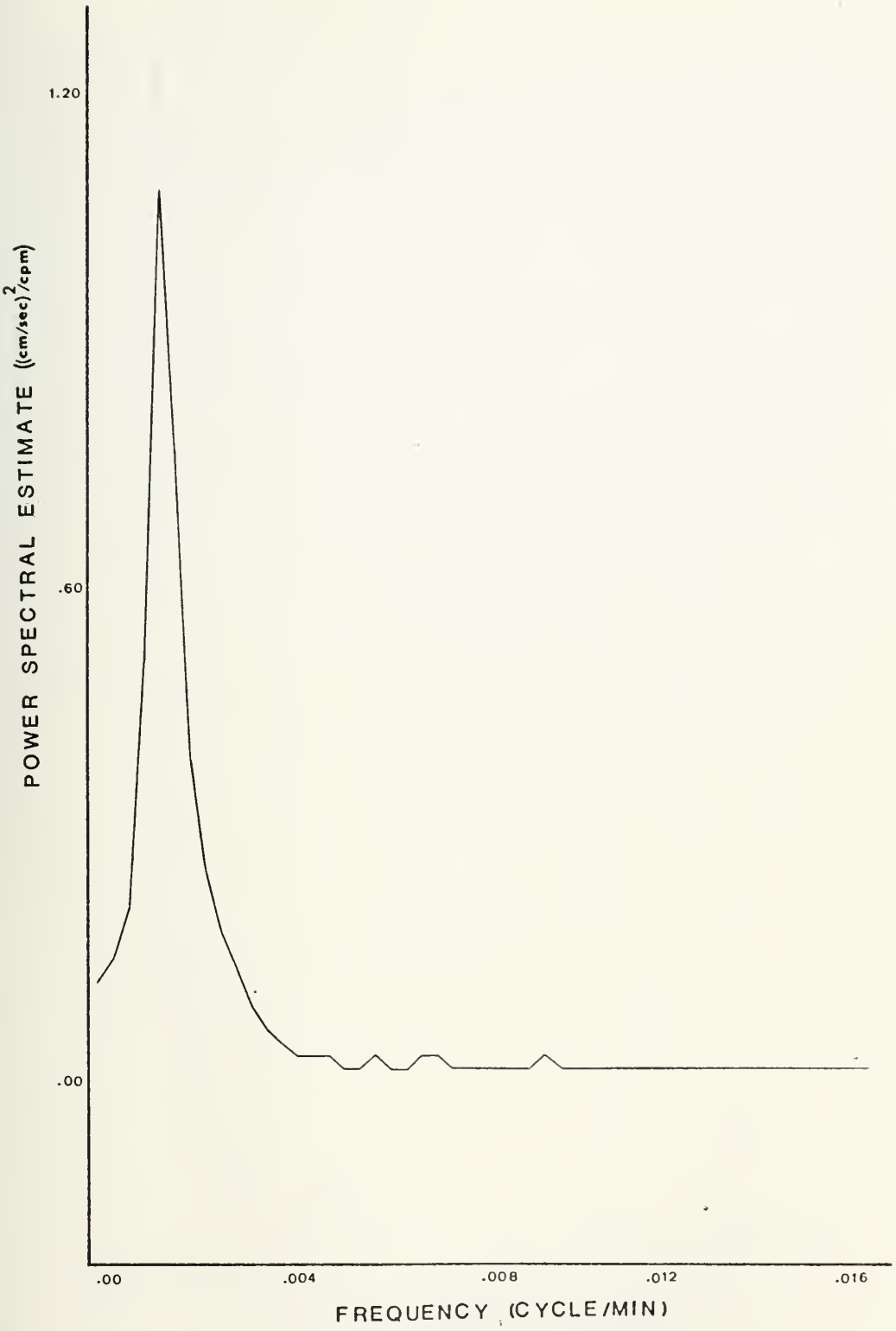


Fig. 34. Power Spectral Estimate, Cross-Canyon Component 60 m above bottom

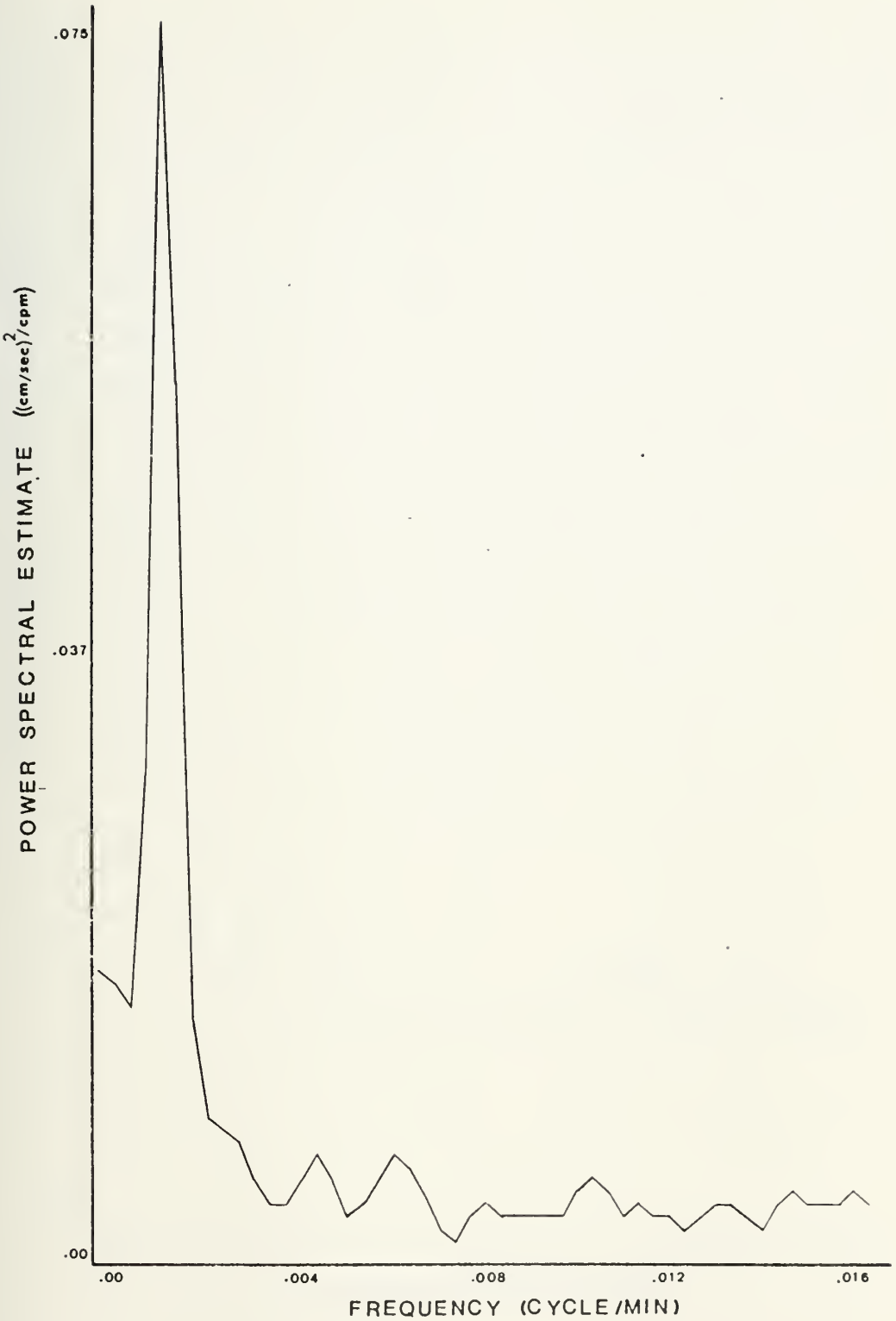


Fig. 35. Power Spectral Estimate, Up-Canyon Component 30 m above bottom

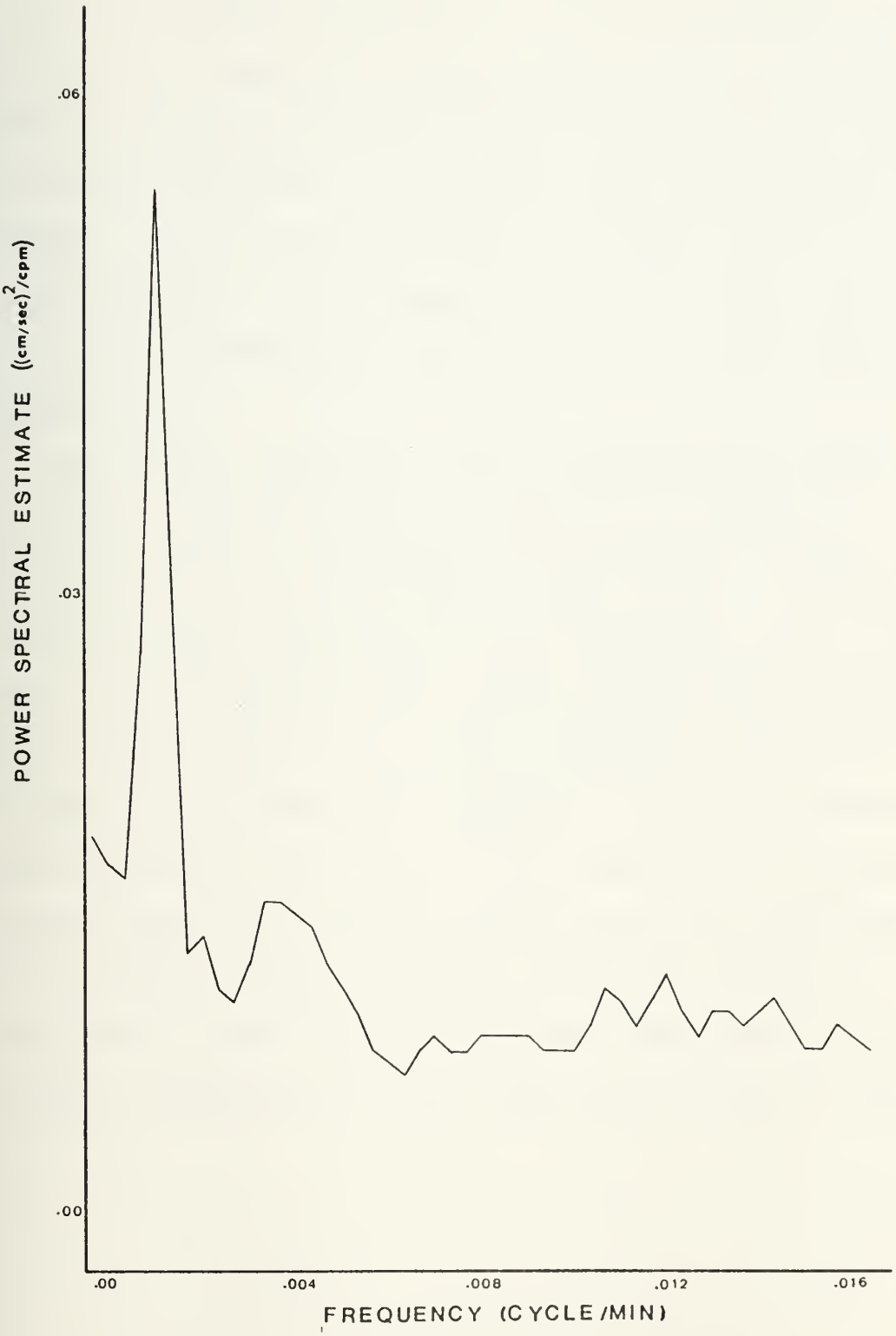


Fig. 36. Power Spectral Estimate, Cross-Canyon Component 30 m above bottom

Power spectral estimates for the 30 m up-canyon and 60 m cross-canyon components are very clean, each with a dominant peak at a period of 12.4 hr. The 30 m cross-canyon spectrum also shows this peak, but has more noise in the higher frequencies. The 12.4-hr peak does not appear in the 60 m up-canyon spectrum; the highest energy in this spectrum, which is far noisier than the others, occurs at a period of approximately 24 hrs.

The frequency content of the component pairs previously listed was clearly visible in the cross-covariances. Again, the 12.4-hr period was prominent, particularly in the up-canyon and cross-canyon component pairs. Coherences were low and noisy. The cross-covariance of the 30 m up-canyon and 60 m cross-canyon records also showed the prominent 12.4-hr period for most of the record, but values of the cross-covariance function hovered near zero for one segment of the record. Although there are several possible causes for this phenomenon, such as phase changes or effects indirectly related to a change from even to uneven tides, no obvious solution to the problem presents itself except to use longer time series in the future.

V. CONCLUSIONS

The directional trends recorded, particularly the very strong cross-canyon component of the 60 m above-bottom record, further support the contention of Shepard and Marshall [1973b] that there may be a level above the bottom beyond which current direction is reversed. The cross-canyon flow may also be due to the intrusion of currents along the continental slope into the canyon. Since the coherence values are lower than might be expected from two current meters separated by only 30 m, it is possible that the upper instrument was in the vicinity of a near-bottom boundary layer, perhaps caused by a moving suspension of sediments in the bottom layer. It is also possible that the coherence has degenerated from the effects of noise.

Previous investigators have reported decreasing current speeds with distance above the bottom. The higher speeds and volume transport values obtained from the instrument 60 m above the bottom were therefore unexpected, but not unreasonable. One would expect near-bottom current speeds to be lower because of bottom friction. Continuous down-slope sediment transport could be a factor contributing to higher current speeds very near the bottom. If, however, the 60 m currents are associated with along-slope currents rather than down-canyon flow, the higher speeds are not surprising.

The 12.4-hr oscillations revealed in the spectral analysis are undoubtedly due to tides or tidally influenced phenomena.

The cause or causes of the shorter period oscillations, however, remain unidentified. These shorter periods of oscillation are of the proper order of magnitude for internal waves and the differing amounts of energy occurring in the higher frequency portions of the up-canyon spectral estimates could be explained by the diverse mode patterns associated with internal waves.

Current flow 30 m above the bottom is predominantly along the canyon axis and appears to be tidally-driven. This current is probably related to a steady down-canyon transport of suspended sediment. At 60 m above the bottom the current is a well established cross-canyon flow that is only slightly perturbed by up- and down-canyon tidal oscillations. This can be seen in the progressive vector diagram (Fig. 10). Coherence between the two current meter records is low and noise-like, and the two signals are essentially not correlated.

Further investigations to define the complex nature of current flow in submarine canyons are clearly warranted. Verification of the above hypotheses could be accomplished by a series of multiple instrument/multiple array investigations with current meters deployed at 3 m, 30 m, 60 m, and 90 m above the bottom and arrays spaced at 4 km intervals, approximately one-fourth the wavelength of an internal wave, along the canyon axis. The arrays should be deployed for at least 30 days to include a complete tidal cycle.

```
C     PROGRAM SUBMARINE CANYON PROVIDES ELEMENTARY STATISTICS FOR
C     TIME SERIES' OF CURRENT SPEED, CURRENT DIRECTION, AND
C     TEMPERATURE.  MEANS ARE COMPUTED HOURLY, DAILY, AND FOR THE
C     ENTIRE SERIES.  A HISTOGRAM IS PROVIDED DAILY AND FOR EACH
C     SERIES.  VARIANCES AND STANDARD DEVIATIONS ARE COMPUTED FOR
C     EACH SERIES.
CC
C
      DIMENSION DATE(3), DATO(3), TIME(5000), T(5000), S(5000), D(5000),
     1 M(5000), AS1(8), MD1(8)
      REAL LABEL /4H    /
C
CC    IND = NUMBER OF DATA SETS
C
      IND = 1
C
      DO 250 III=1,IND
      CLOCK = ITIME(0)*0.01
C
CC    CONTROL CARD INPUT:
C
      READ (5,280) NN,NO,NT,NA,NH,NP,PN,NW,PW,ICOR,IMO,DATE,DATO,INKTS
C
CC    ENTER WITH:  NN=NUMBER OF DATA POINTS.  CALL DRAW MUST BE
CC                    ADJUSTED TO TOTAL OF NN POINTS (I4).
CC                 NO=DAY OF FIRST OBSERVATION (I2).
CC                 NT=TIME OF FIRST OBSERVATION (I4).
CC                 NA=LARGEST NT LESS THAN 2400 (I4).
CC                 NH=HOUR FRACTIONATION (IN MINUTES) OF FIRST
CC                    OBSERVATION (I2).
CC                 NP=LATITUDE DEGREES (I2).
CC                 PN=LATITUDE MINUTES (F6.2).
CC                 NW=LONGITUDE DEGREES (I3).
CC                 PW=LONGITUDE MINUTES (F6.2).
CC                 ICOR=DIRECTION CORRECTION FOR MAGNETIC VARIATION (I3)
CC                 IMO=LAST DAY OF MONTH (I3).
CC                 DATE=MONTH OF OBSERVATION (3A4).
CC                 DATO=DATE PLUS ONE MONTH (3A4).
CC                 INKNTS=1 CONVERTS DATA IN KNOTS TO CM/SEC.
CC
CC    DEL = SAMPLING INTERVAL IN MINUTES.
C
      DEL = 5.0
C
CC    SI PLUS 1.0 = NUMBER OF SAMPLES PER HOUR
CC
      SI = ((60.0/DEL)-1.0)
      TIME(1) = 0.
```

```
      NODRW = 0                                                          480
C                                                                        490
CC    NODRW = 1 IF NO GRAPHS ARE DESIRED.                                500
C                                                                        510
      L = 0                                                              520
      NZ = 0                                                             530
      IDAY = 1                                                           540
      WRITE (6,290) NP,PN,NW,PW,NO,NT,DATE                               550
      WRITE (6,300)                                                      560
      WRITE (6,310) NO,NT,DATE                                           570
C                                                                        580
CC    INPUT TEMPERATURE, SPEED, AND DIRECTION TIME SERIES.               590
CCC                                                                      600
C                                                                        610
      DO 100 I=1,NN,5                                                    620
      READ (5,320,END=120) (T(I+K-1),S(I+K-1),M(I+K-1),K=1,5)            630
  100 CONTINUE                                                           640
C                                                                        650
CCC                                                                      660
CCC   CONVERT TO CM/SEC IF INPUT IS IN KNOTS (INKTS=1).                  670
C                                                                        680
      IF (INKTS.NE.1) GO TO 120                                          690
C                                                                        700
      DO 110 I=1,NN                                                      710
  110 S(I) = S(I)*51.479                                                 720
C                                                                        730
  120 CONTINUE                                                           740
C                                                                        750
CC    COMPUTE HOURLY AND SERIES MEANS.                                   760
CC    N1 IS A COUNTER FOR ACCUMULATING AVERAGES BY 8'S.                  770
C                                                                        780
      N1 = 0                                                             790
C                                                                        800
      DO 220 I=1,NN                                                      810
C                                                                        820
CCC   ADJUST DIRECTION IF REQUIRED.                                      830
C                                                                        840
      M(I) = M(I)+ICOR                                                   850
      IF (M(I)-0.) 130,140,140                                           860
  130 M(I) = M(I)+360                                                    870
  140 CONTINUE                                                           880
      IF (M(I).LT.360) GO TO 150                                         890
      M(I) = M(I)-360                                                    900
  150 CONTINUE                                                           910
      N = I                                                              920
      IF (T(I).EQ.1.) GO TO 220                                          930
      WRITE (6,330) TIME(I),T(I),S(I),M(I),I                             940
      IF (L.LT.SI) GO TO 210                                             950
```

```
C                                                                       960
CC      SI PLUS 1.0 IS THE NUMBER OF SAMPLES PER HOUR.  THIS            970
CC      FIGURE IS INTERNALLY ADJUSTED FOR DIFFERENT SAMPLING            980
CC      INTERVALS IN ORDER TO COMPUTE HOURLY MEANS.                     990
C                                                                      1000
        NT = NT+100                                                    1010
        IF (NT.LE.NA) GO TO 160                                        1020
        NT = 0000+NH                                                   1030
        NO = NO+1                                                      1040
        IMN = I-NZ                                                     1050
C                                                                      1060
CC      PROGRAM COMPUTES STATISTICS AT END OF EACH DAY.                1070
C                                                                      1080
        CALL DAY (T,S,M,IMN,I,1,DTAV,DSAV,DDAV)                        1090
        IDDAV = IFIX(DDAV)                                             1100
        WRITE (6,260) IDAY,DTAV,DSAV,IDDAV                             1110
        IDAY = IDAY+1                                                  1120
        NZ = 0                                                         1130
C                                                                      1140
CC      IF MONTH CHANGES, REPLACE THE DATE.                            1150
C                                                                      1160
  160 IF (NO.LE.IMO) GO TO 180                                         1170
        NO = 1                                                         1180
C                                                                      1190
        DO 170 J=1,3                                                   1200
  170 DATE(J) = DATO(J)                                                1210
C                                                                      1220
  180 CONTINUE                                                         1230
        HR = TIME(I)/60                                                1240
        IML = I-L                                                      1250
C                                                                      1260
CC      CALL SUBROUTINES FOR HOURLY MEANS.                             1270
C                                                                      1280
        N1 = N1+1                                                      1290
        CALL MEAN (T,IML,I,AT)                                         1300
        CALL MEAN (S,IML,I,AS)                                         1310
        AS1(N1) = AS                                                   1320
        CALL MEAND (M,IML,I,S,AVG)                                     1330
        MD = IFIX(AVG)                                                 1340
        IF (MD.GE.0) GO TO 190                                         1350
        MD = 360+MD                                                    1360
  190 CONTINUE                                                         1370
        MD1(N1) = MD                                                   1380
C                                                                      1390
CC      SPEED AND DIRECTION AVERAGES ACCUMULATED BY 8'S FOR PUNCHED CARD 1400
CC      INPUT INTO PROGRAM VECTOR DRAW.                                1410
C                                                                      1420
        IF (N1.LT.8) GO TO 200                                         1430
```

```
      N1 = 0                                                                1440
      WRITE (7,270) (AS1(K),MD1(K),K=1,8)                                   1450
  200 CONTINUE                                                              1460
C                                                                           1470
CC    WRITE OUT HOURLY MEANS.                                               1480
C                                                                           1490
      WRITE (6,340) NO,NT,DATE,HR,AT,AS,MD                                  1500
      L = -1                                                                1510
  210 TIME(I+1) = TIME(I)+DEL                                               1520
      NZ = NZ+1                                                             1530
      L = L+1                                                               1540
  220 CONTINUE                                                              1550
C                                                                           1560
C                                                                           1570
      WRITE (7,270) (AS1(K),MD1(K),K=1,8)                                   1580
      N = NN                                                                1590
C                                                                           1600
CC    COMPUTE THE TIME SERIES MEANS.                                        1610
C                                                                           1620
      CALL MEAN (T,1,N,TAT)                                                 1630
      CALL MEAN (S,1,N,TAS)                                                 1640
      CALL MEAND (M,1,N,S,AVG)                                              1650
      MMD = IFIX(AVG)                                                       1660
      IF (MMD.GE.0) GO TO 230                                               1670
      MMD = 360+MMD                                                         1680
  230 CONTINUE                                                              1690
      WRITE (6,350) TAT,TAS,MMD                                             1700
C                                                                           1710
      DO 240 I=1,N                                                          1720
      D(I) = FLOAT(M(I))                                                    1730
  240 CONTINUE                                                              1740
C                                                                           1750
CC                                                                          1760
CC    CALL HISTO SUBROUTINE FOR TIME SERIES HISTOGRAM.                      1770
C                                                                           1780
      CALL HISTO (0.,10.,20,T,NN,1,NODRW)                                   1790
      CALL HISTO (0.,75.,15,S,NN,1,NODRW)                                   1800
      CALL HISTO (0.,360.,36,D,NN,1,NODRW)                                  1810
C                                                                           1820
CC    CALL SUBROUTINE POWER FOR RMS, VARIANCE, AND STANDARD DEVIATIONS.     1830
C                                                                           1840
      CALL POWER (DEL,NN,T,S,D,100)                                         1850
      CLOCK = ITIME(0)*0.01-CLOCK                                           1860
      WRITE (6,360) CLOCK                                                   1870
  250 CONTINUE                                                              1880
C                                                                           1890
      STOP                                                                  1900
C                                                                           1910
```

```
  260 FORMAT (5X,'DAY ',I2,' STATISTICS:  AVGDAYTEMP=',F6.2,3X,                1920
     1 'AVGDAYSPD=',F5.2,3X,'AVGDAYDIR=',I4,//)                               1930
  270 FORMAT (8(F5.2,I4))                                                     1940
  280 FORMAT (I4,I2,2I4,2I2,F6.2,I3,F6.2,2I3,3A4,3A4,I2)                      1950
  290 FORMAT (1H1,T40,'CURRENT METER DATA OBTAINED IN MONTEREY CANYON',       1960
     1 ///,5X,'METER POSITION:  ',I2,F6.2,' N  ',I3,F6.2,' W  ',              1970
     2 /,5X,'ZERO TIME:  ',I2,I4,'(LOCAL)',3A4,                               1980
     3 //,5X,'TIME IN MINUTES',                                               1990
     4 /,5X,'TEMPERATURE IN DEGREES CENTIGRADE',                              2000
     5 /,5X,'CURRENT SPEED IN CENTIMETERS PER SECOND',                        2010
     6 /,5X,'CURRENT DIRECTION IN DEGREES TRUE',////)                         2020
  300 FORMAT (15X,'TIME',10X,'TEMPERATURE',6X,'CURRENT SPEED',4X,             2030
     1 'CURRENT DIRECTION')                                                   2040
  310 FORMAT (1H0,5X,I2,I4,3A4)                                               2050
  320 FORMAT (5(F5.1,F5.2,I4))                                                2060
  330 FORMAT (10X,F10.2,13X,F4.1,15X,F5.2,14X,I3,5X,I5,5X,I5)                 2070
  340 FORMAT (1H0,I3,I4,3A4,2X,F5.1,'HRS',4X,'MEAN TEMP:',                    2080
     1 F6.2,4X,'MEAN SPEED:',F5.2,2X,'MEAN DIR:',I3,//)                       2090
  350 FORMAT (1H0,11X,'MEANS FOR THIS RECORD:    TEMP:',F6.2,2X,'SPEED:',     2100
     1 F5.2,2X,'DIRECTION:',I3)                                               2110
  360 FORMAT (///,T80,'ELAPSED COMPUTING TIME=',F15.7,'SECONDS')              2120
      END                                                                     2130
```



```
      SUBROUTINE MEAN (A,J,M,AVG)                                              10
C                                                                              20
C     SUBROUTINE MEAN COMPUTES THE ARITHMETIC MEAN OF ANY                      30
C     INPUT PARAMETER.                                                         40
C                                                                              50
      DIMENSION A(5000)                                                        60
      AVG = 0.0                                                                70
      SUM = 0.0                                                                80
      KK = M-J+1                                                               90
      FKK = FLOAT(KK)                                                         100
C                                                                             110
      DO 100 K=J,M                                                            120
  100 SUM = SUM+A(K)                                                          130
C                                                                             140
      AVG = SUM/FKK                                                           150
      RETURN                                                                  160
      END                                                                     170


      SUBROUTINE MEAND (LL,J,M,S,AVG)                                          10
C                                                                              20
C     SUBROUTINE MEAND COMPUTES THE MEANS OF DIRECTION INPUTS AS COMPASS        30
```

```
C       HEADINGS BY SUMMING SINES AND COSINES;  CONVERT TO VECTOR WITH          40
C       SPEED THEN NORMALIZE AND FIND THE ARCTANGENT.  THIS PROCEDURE          50
C       IS NECESSARY TO CIRCUMVENT THE 000 TO 360 DISCONTINUITY.               60
C                                                                              70
        DIMENSION LL(5000), S(5000)                                            80
        SUM1 = 0.0                                                             90
        SUM2 = 0.0                                                            100
C                                                                             110
        DO 110 K=J,M                                                          120
        AK = LL(K)*0.01745329                                                 130
        IML = M-J+1                                                           140
        IF (S(K).GT.0.0) GO TO 100                                            150
C                                                                             160
C       SPEED NOT AVAILABLE.  READ FROM DATA CARD AS S(K)=0.0.                170
C       INSERT FALSE VALUE TO ELIMINATE DIVISION BY ZERO.                     180
C                                                                             190
        S(K) = 0.001                                                          200
  100 CONTINUE                                                                210
        SUM1 = SUM1+S(K)*SIN(AK)                                              220
        SUM2 = SUM2+S(K)*COS(AK)                                              230
  110 CONTINUE                                                                240
C                                                                             250
        U = SUM1/FLOAT(IML)                                                   260
        V = SUM2/FLOAT(IML)                                                   270
        AVG = ATAN2(U,V)                                                      280
        AVG = AVG/.01745329                                                   290
        RETURN                                                                300
        END                                                                   310


        SUBROUTINE HISTO (A,Z,K,X,L,M,NODRW)                                   10
C                                                                              20
C       SUBROUTINE HISTO OBTAINS HISTOGRAM, PERCENT OF DATA PER INTERVAL,      30
C       PROBABILITY DENSITY, AND PROBABILITY DISTRIBUTION.                     40
C       ENTER WITH:  A=LOWER BOUND                                             50
C                    Z=UPPER BOUND                                             60
C                    K=NUMBER OF INTERVALS (MAX=50)                            70
C                    X=VARIABLE NAME                                           80
C                    L=NUMBER OF VARIABLES (MAX=3000)                          90
C                    NODRW=1 IF GRAPH NOT DESIRED                             100
C                                                                             110
        DIMENSION N(5000), X(5000), P(55), PP(55), D(55), PD(55), B(5000)     120
        REAL *8ITITLA(12)                                                     130
        REAL LABEL /4H    /                                                   135
        IF (NODRW.EQ.1) GO TO 100                                             140
        READ (5,250) (ITITLA(I),I=1,12)                                       150
C                                                                             160
```

```
C      EACH TITLE (THERE ARE THREE) CONSISTS OF TWO CARDS WITH NO MORE
C      THAN 48 CHARACTERS EACH.
C
  100 CONTINUE
      WRITE (6,220)
      LL = 0
      C = (Z-A)/FLOAT(K)
      D(1) = A
      KP1 = K+1
      KP2 = K+2
C
      DO 110 I=2,KP2
      IM1 = I-1
  110 D(I) = A+IM1*C
C
      SUMP = 0.0
C
      DO 120 I=1,KP2
  120 B(I) = 0
C
      LLL = M+L
C
      DO 160 J=M,LLL
C
      DO 150 I=1,KP2
      IP1 = I+1
      IF (X(J).LT.D(I)) GO TO 150
      IF (X(J).GE.D(I)) GO TO 130
  130 IF (X(J).LT.D(IP1)) GO TO 140
      GO TO 150
  140 B(I) = B(I)+1
      LL = LL+1
      IF (X(J).LE.Z) GO TO 150
      LL = LL-1
  150 CONTINUE
C
  160 CONTINUE
C
C
      DO 170 I=1,KP2
  170 P(I) = B(I)/FLOAT(LL)
C
C
      DO 180 I=1,KP2
  180 PP(I) = P(I)/C
C
C
      DO 190 I=1,KP2
```

```
      SUMP = SUMP+PP(I)                                                    650
  190 PD(I) = SUMP*C                                                       660
C                                                                          670
C                                                                          680
      DO 200 I=1,KP1                                                       690
      IP1 = I+1                                                            700
      N(I) = IFIX(B(I))                                                    710
      WRITE (6,230) I,D(I),D(IP1),N(I),P(I),PP(I),PD(I)                    720
  200 CONTINUE                                                             730
C                                                                          740
      WRITE (6,240) LL                                                     750
C                                                                          760
      DO 210 I=1,KP1                                                       770
  210 D(I) = D(I)+(C/2.)                                                   780
C                                                                          790
      IF (NODRW.EQ.1) RETURN                                               800
      CALL DRAW (KP1,D,B,0,0,LABEL,ITITLA,0,0,0,0,0,0,3,5,0,LAST)          810
      RETURN                                                               820
C                                                                          830
  220 FORMAT (1H0,10X,'INTERVAL',11X,'OCCURRENCES',3X,'% DATA',3X,          840
     1 'DENSITY',3X,'DISTRIBUTION',//)                                     850
  230 FORMAT (4X,I2,F7.2,' - ',F7.2,4X,I8,3F12.3)                          860
  240 FORMAT (//,8X,'NUMBER OF POINTS:  ',I8)                              870
  250 FORMAT (6A8)                                                         880
      END                                                                  890


      SUBROUTINE POWER (DEL,N,X,Y,Z,L)                                      10
C                                                                           20
CC    SUBROUTINE POWER COMPUTES THE MEANS, MEAN SQUARED VALUES, AND         30
C     STANDARD DEVIATIONS OF THREE INPUT TIME SERIES.                       40
      DIMENSION XM(5000), X(5000), Y(5000), Z(5000)                         50
C     ENTER WITH:  DEL=SAMPLING INTERVAL IN MINUITES                        60
CC                 N=NUMBER OF SAMPLES (MAX.=3000)                        70
CC                 X=VARIABLE OF THE FIRST SERIES                         80
CC                 Y=VARIABLE OF THE SECOND SERIES                        90
CC                 Z=VARIABLE OF THE THIRD SERIES                        100
CC                 L=NUMBER OF LAGS (MAX.=200)                           110
CC    CALCULATION OF SERIES MEAN VALUE                                    120
C                                                                         130
      SUM1 = 0.0                                                          140
      SUM2 = 0.0                                                          150
      SUM3 = 0.0                                                          160
C                                                                         170
      DO 100 I=1,N                                                        180
      SUM1 = SUM1+X(I)                                                    190
      SUM2 = SUM2+Y(I)                                                    200
```

```
  100 SUM3 = SUM3+Z(I)                                                  210
C                                                                       220
      XBAR = SUM1/N                                                     230
      YBAR = SUM2/N                                                     240
      ZBAR = SUM3/N                                                     250
      WRITE (6,150) XBAR,YBAR,ZBAR                                      260
C                                                                       270
C     TRANSFORMATION TO ZERO MEAN VALUE                                 280
C                                                                       290
C                                                                       300
      DO 110 I=1,N                                                      310
      XM(I) = X(I)-XBAR                                                 320
  110 CONTINUE                                                          330
C                                                                       340
      CALL MEAN (XM,1,N,AVG)                                            350
      WRITE (6,160) AVG                                                 360
C                                                                       370
      DO 120 I=1,N                                                      380
      XM(I) = Y(I)-YBAR                                                 390
  120 CONTINUE                                                          400
C                                                                       410
      CALL MEAN (XM,1,N,AVG)                                            420
      WRITE (6,160) AVG                                                 430
C                                                                       440
      DO 130 I=1,N                                                      450
      XM(I) = Z(I)-ZBAR                                                 460
  130 CONTINUE                                                          470
C                                                                       480
      CALL MEAN (XM,1,N,AVG)                                            490
      WRITE (6,160) AVG                                                 500
C                                                                       510
C     CALCULATION OF THE MEAN SQUARE VALUE                              520
C                                                                       530
      SUM1 = 0.0                                                        540
      SUM2 = 0.0                                                        550
      SUM3 = 0.0                                                        560
C                                                                       570
      DO 140 I=1,N                                                      580
      SUM1 = SUM1+(X(I)-XBAR)**2                                        590
      SUM2 = SUM2+(Y(I)-YBAR)**2                                        600
      SUM3 = SUM3+(Z(I)-ZBAR)**2                                        610
  140 CONTINUE                                                          620
C                                                                       630
      XMS = SUM1/N                                                      640
      YMS = SUM2/N                                                      650
      ZMS = SUM3/N                                                      660
      WRITE (6,170) XMS,YMS,ZMS                                         670
C                                                                       680
```

```
C      CALCULATION OF THE STANDARD DEVIATION                                690
C                                                                           700
       XTEMP = SUM1/(N-1)                                                   710
       YTEMP = SUM2/(N-1)                                                   720
       ZTEMP = SUM3/(N-1)                                                   730
       SX = SQRT(XTEMP)                                                     740
       YX = SQRT(YTEMP)                                                     750
       ZX = SQRT(ZTEMP)                                                     760
       WRITE (6,180) SX,YX,ZX                                               770
       RETURN                                                               780
C                                                                           790
  150 FORMAT (T10,'SAMPLE MEANS:',//,T35,'XBAR=  ',F10.3,/,T35,'YBAR=  '    800
     1,F10.3,/,T35,'ZBAR=  ',F10.3,///)                                     810
  160 FORMAT (T40,F30.10)                                                   820
  170 FORMAT (T10,'MEAN SQUARE VALUES:',//,T35,'XMSQ=  ',F10.3,/,T35,       830
     1 'YMSQ=  ',F10.3,/,T35,'ZMSQ=  ',F10.3///)                            840
  180 FORMAT (T10,'STANDARD DEVIATIONS:',//,T35,'XSTDDEV=  ',F10.5,/,T35    850
     1,'YSTDDEV=  ',F10.5,/,T35,'ZSTDDEV=  ',F10.5,///)                     860
       END                                                                  870


       SUBROUTINE DAY (T,S,M,J,K,NODRW,DTAV,DSAV,DDAV)                       10
C                                                                            20
C      SUBROUTINE DAY UTILIZES PREVIOUS SUBROUTINES TO OBTAIN                30
C      DAILY STATISTICS.                                                     40
C                                                                            50
       DIMENSION DH(5000), T(5000), S(5000), M(5000)                         60
C                                                                            70
C      ENTER WITH:  T=TEMPERATURE SERIES                                     80
C                   S=SPEED SERIES                                           90
C                   M=DIRECTION SERIES                                      100
C                   J=DAY START OBSERVATION NUMBER                          110
C                   K=TOTAL OBSERVATIONS IN THE SERIES                      120
C                   NODRW=1 IF GRAPH NOT DESIRED                            130
C                                                                           140
       CALL MEAN (T,J,K,DTAV)                                               150
       CALL MEAN (S,J,K,DSAV)                                               160
       CALL MEAND (M,J,K,S,DDAV)                                            170
       IF (DDAV.GE.0) GO TO 100                                             180
       DDAV = DDAV+360                                                      190
  100 CONTINUE                                                              200
       JP1 = J+1                                                            210
       KK = K-JP1                                                           220
       WRITE (6,120) JP1,K,KK                                               230
C                                                                           240
       DO 110 I=JP1,K                                                       250
  110 DH(I) = FLOAT(M(I))                                                   260
```

```
C                                                                       270
      CALL HISTO (0.,10.,20,T,KK,J,NODRW)                               280
      CALL HISTO (0.,75.,15,S,KK,J,NODRW)                               290
      CALL HISTO (0.,360.,36,DH,KK,J,NODRW)                             300
      RETURN                                                            310
C                                                                       320
  120 FORMAT (2X,'DAILY HISTO FROM',I4,' TO ',I4,' TOTAL: ',I4,'PTS',//) 330
      END                                                               340
```

```
C      PROGRAM COMPOSITE DRAW PROVIDES A COMBINED TEMPERATURE, CURRENT
CC     SPEED, AND CURRENT DIRECTION GRAPH.
C
       DIMENSION T(5000), TIME(5000), S(5000), M(5000), A(5000), B(5000),
      1 C(5000), TNEW(300)
       REAL *8ITITLE(12)
       REAL *8JTITLE(12)
       REAL *8KTITLE(12)
       REAL LABEL /4H    /
C
CC     ND = NUMBER OF DATA SETS
CC     INKTS=1 CONVERTS DATA IN KNOTS TO CM/SEC
C
       READ (5,170) ND,INKTS
       WRITE (6,180) ND
C
C
       DO 160 J=1,ND
       WRITE (6,190) J
C
CC     NN = NUMBER OF DATA POINTS.
C
       READ (5,200) NN
       WRITE (6,210) NN
C
CC     DEL IS THE SAMPLING INTERVAL IN HOURS.
C
       DEL = 0.0833
       WRITE (6,220) DEL
       TIME(1) = 0
       NODRW = 0
       WRITE (6,230) NODRW
C
       DO 100 I=1,NN,5
       READ (5,240) (T(I+K-1),S(I+K-1),M(I+K-1),K=1,5)
  100 CONTINUE
C
C
CC     CONVERT TO CM/SEC IF DATA INPUT IS IN KNOTS (INKTS=1).
C
       IF (INKTS.NE.1) GO TO 120
C
       DO 110 I=1,NN
  110 S(I) = S(I)*51.479
C
  120 CONTINUE
       WRITE (6,250)
C
```

```
      DO 130 I=1,NN                                                     480
      F = I                                                             490
      TIME(I+1) = F*DEL                                                 500
C                                                                       510
CC    SCALE DATA FOR GRAPHICAL DISPLAY.                                 520
C                                                                       530
      A(I) = (T(I)-5.5)                                                 540
      B(I) = S(I)                                                       550
      C(I) = M(I)                                                       560
  130 CONTINUE                                                          570
C                                                                       580
C                                                                       590
      WRITE (6,260)                                                     600
C                                                                       610
CC    PROVIDE DATA SET TITLE FOR EACH CALL DRAW.  TITLE IS TWO CARDS    620
CC    WITH NO MORE THAN 48 CHARACTERS EACH (6A8).                       630
C                                                                       640
      NOD = NN/288                                                      650
      NREM = 288*NOD                                                    660
      IREM = NN-NREM                                                    670
      NREM = NREM+1                                                     680
      READ (5,270) (JTITLE(I),I=1,12)                                   690
      READ (5,270) (KTITLE(I),I=1,12)                                   700
C                                                                       710
      DO 150 JJ=1,NOD                                                   720
      KK = 288*(JJ-1)+1                                                 730
      TIME1 = TIME(KK)                                                  740
C                                                                       750
      DO 140 II=1,288                                                   760
      TNEW(II) = TIME(KK+II-1)-TIME1                                    770
  140 CONTINUE                                                          780
C                                                                       790
      CALL DRAW (288,TNEW,B(KK),0,0,LABEL,JTITLE,                       800
     14.,5.,0,0,2.2,7,6,0,LAST)                                         810
      CALL DRAW (288,TNEW,C(KK),0,0,LABEL,KTITLE,                       820
     14.,60.,0,0,2,2,7,6,0,LAST)                                        830
  150 CONTINUE                                                          840
C                                                                       850
      CALL DRAW (IREM,TNEW,B(NREM),0,0,LABEL,JTITLE,                    860
     14.,5.,0,0,2,2,7,6,0,LAST)                                         870
      CALL DRAW (IREM,TNEW,C(NREM),0,0,LABEL,KTITLE,                    880
     14.,60.,0,0,2,2,7,6,0,LAST)                                        890
  160 CONTINUE                                                          900
C                                                                       910
      RETURN                                                            920
C                                                                       930
  170 FORMAT (2(I6))                                                    940
  180 FORMAT (//,5X,I4,' DATA SETS')                                    950
```

```
190 FORMAT (//,5X'DATA SET NUMBER',I4)                                  960
200 FORMAT (I6)                                                         970
210 FORMAT (//,5X,'NN =',1X,I4)                                         980
220 FORMAT (5X,'DEL =',1X,F7.4)                                         990
230 FORMAT (5X,'NODRW =',1X,I4)                                        1000
240 FORMAT (5(F5.1,F5.2,I4))                                           1010
250 FORMAT (//,1X,'DATA INPUT COMPLETED')                              1020
260 FORMAT (//,5X,'DATA CONVERTED FOR GRAPHICAL DISPLAY')              1030
270 FORMAT (6A8)                                                       1040
    END                                                                1050
```

```
C      PROGRAM VECTOR DRAW PROVIDES A PROGRESSIVE VECTOR DIAGRAM.  THE
C      DIAGRAM REPRESENTS THE SUMMATION OF VECTORS MADE UP OF CURRENT
C      SPEED AND CURRENT DIRECTION FOR ONE HOUR PERIODS.  INPUT VALUES
C      ARE OBTAINED FROM PROGRAM CURRENT.  THE PROGRESSIVE VECTOR DIAGRAM
C      INDICATES THE NET TRANSPORT OF WATER AND ITS DIRECTION OF MOVEMENT
C
C
      DIMENSION SPD(400), DIR(400), X(400), Y(400), A(400), B(400),
     1 XA(400), YB(400)
      REAL *8TVT
      REAL LABEL /4H    /
      REAL *8ITITLE(12)
C
CC    N = NUMBER OF DATA POINTS
C
      READ (5,130) N
      WRITE (6,140) N
      READ (5,150) ITITLE
      REAL *8LABEA/8H/
C
CC    READ IN DATA
C
      READ (5,160) (SPD(I),DIR(I),I=1,N)
C
CCC   CONVERT SPEED DATA TO KNOTS
C
      DO 100 I=1,N
  100 SPD(I) = SPD(I)/51.479
C
CC
CC    PRINT OUT DATA
C
      WRITE (6,170)
      WRITE (6,180) (SPD(I),DIR(I),I,I=1,N)
C
CC    INITILIZE
C
      X(1) = 0.
      Y(1) = 0.
      A(1) = 0.
      B(1) = 0.
      N1 = N+1
      WRITE (6,190)
C
      DO 110 I=2,N1
C
C     CONVERT DIRECTION IN DEGREES TO DIRECTION IN RADIANS BY
```

```
C      MULTIPLYING BY 0.01745.                                                  480
C                                                                               490
C                                                                               500
C      CONVERT CURRENT VECTOR (SPEED AND DIRECTION) INTO X AND Y                510
C      COMPONENTS.                                                              520
C                                                                               530
       X(I) = SPD(I-1)*SIN(DIR(I-1)*0.01745)                                    540
       Y(I) = SPD(I-1)*COS(DIR(I-1)*0.01745)                                    550
C                                                                               560
C      A AND B ARE THE SUMS OF INDIVIDUAL X AND Y VALUES.                       570
C                                                                               580
       A(I) = X(I)+A(I-1)                                                       590
       B(I) = Y(I)+B(I-1)                                                       600
       WRITE (6,200) X(I),Y(I),A(I),B(I)                                        610
  110 CONTINUE                                                                  620
C                                                                               630
       K = 1                                                                    640
C                                                                               650
       DO 120 I=1,N1,24                                                         660
C                                                                               670
C      XA AND YB WILL BE THE VALUES OF A AND B AT THE END OF A 24 HOUR          680
C      PERIOD.                                                                  685
C                                                                               690
       XA(K) = A(I)                                                             700
       YB(K) = B(I)                                                             710
       K = K+1                                                                  720
  120 CONTINUE                                                                  730
C                                                                               740
       N2 = N1/24                                                               750
C                                                                               760
C      CALL DRAW WILL DRAW PROGRESSIVE VECTOR DIAGRAMS USING THE CALCOMP        770
C      PLOTTER.  IF THE NUMBER OF DATA POINTS IS LESS THAN 25 THE SECOND        780
C      DRAW STATEMENT SHOULD BE DELETED BECAUSE THIS STATEMENT INDICATES        790
C      AN 'X' EVERY 24 HOURS AND MUST HAVE AT LEAST TWO POINTS IN ORDER         800
C      TO FUNCTION.                                                             805
C                                                                               810
       CALL DRAW (N1,A,B,1,0,LABEL,ITITLE,0.,0.,0,0,0,0,9,10,0,LAST)            820
       CALL DRAW (N2,XA,YB,3,1,LABEA,ITITLE,0.,0.,0,0,0,0,9,10,0,LAST)          830
       WRITE (6,190)                                                            840
       CALL PLOTP (X,Y,N1,0)                                                    850
       WRITE (6,190)                                                            860
       CALL PLOTP (A,B,N1,1)                                                    870
       CALL PLOTP (XA,YB,N2,3)                                                  880
       WRITE (6,210) A(N1),B(N1)                                                890
C                                                                               900
C      VECTOR SUM IN NAUTICAL MILES.                                            910
C                                                                               920
       VECSUM = SQRT(A(N1)*A(N1)+B(N1)*B(N1))                                   930
```

```
C                                                                       940
C       CONVERT TO METERS.                                              950
C                                                                       960
        VECSUM = VECSUM*(1853.248)                                      970
        WRITE (6,220) VECSUM                                            980
C                                                                       990
C       AREA = ONE SQUARE METER.                                       1000
C                                                                      1010
        AREA = 1.0                                                     1020
        WRITE (6,230) AREA                                             1030
C                                                                      1040
C       TOTAL VOLUME TRANSPORT IN CUBIC METERS.                        1050
C                                                                      1060
        TVT = AREA*VECSUM                                              1070
        WRITE (6,240) TVT                                              1080
C                                                                      1090
C       VOLUME TRANSPORT PER HOUR.                                     1100
C                                                                      1110
        AN = N                                                         1120
        XVT = TVT/AN                                                   1130
        WRITE (6,250) XVT                                              1140
        STOP                                                           1150
C                                                                      1160
  130 FORMAT (I6)                                                      1170
  140 FORMAT (1H1,6X,'NO. OF DATA POINTS = ',I6,///)                   1180
  150 FORMAT (6A8)                                                     1190
  160 FORMAT (8(F5.2,F4.0))                                            1200
  170 FORMAT (7X,'SPEED',3X,'DIRECTION',3X,'DATA PT. NO.',/)           1210
  180 FORMAT (6X,F5.2,6X,F4.0,9X,I4)                                   1220
  190 FORMAT (1H1)                                                     1230
  200 FORMAT (5X,'X= ',F10.4,5X,'Y= ',F10.4,5X,'A= ',F10.4,5X,'B= ',   1240
     1F10.4)                                                           1250
  210 FORMAT (1H1,5X,'FINAL A VALUE= ',F10.4,1X,'N.M.',5X,'FINAL B VALUE 1260
     1= ',F10.4,1X,'N.M.',///)                                         1270
  220 FORMAT (5X,'VECTOR SUM=  ',F10.4,1X,'METERS',///)                1280
  230 FORMAT (5X,'AREA= ',F10.4,1X,'M**2',///)                         1290
  240 FORMAT (5X,'TOTAL VOLUME TRANSPORT= ',1D20.13,1X,'M**3',///)     1300
  250 FORMAT (5X,'VOLUME TRANSPORT PER HOUR= ',F20.4,1X,'M**3/HR',///) 1310
        END                                                            1320
```

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